博 士 論 文

Evaluation on environmental, economic and energy savings of ground source heat pumps in cold region of China

中国寒冷地における地中熱ヒートポンプの環境性、経済性、省エネルギー性に関する評価に関する研究

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EVALUATION ON ENVIRONMENTAL, ECONOMIC AND ENERGY SAVINGS OF GROUND SOURCE HEAT PUMPS IN COLD REGION OF CHINA

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EVALUATION ON ENVIRONMENTAL, ECONOMIC AND ENERGY SAVINGS OF GROUND SOURCE HEAT PUMPS IN COLD REGION OF CHINA

ABSTRACT

China continues to recommend carbon peaking and carbon neutrality, which sets the stage for changes in its economic and social development. Ground source heat pumps (GSHPs) have emerged as a rapidly growing alternative energy source, particularly suitable for the colder regions of northern China. This paper provides a comprehensive overview of the adaptability of ground source heat pumps in cold regions, addresses the challenges associated with soil thermal imbalance, discusses the optimization of heat transfer pore spacing, and emphasizes the environmental, economic, and energy efficiency of ground source heat pumps. Addressing the challenges associated with soil thermal imbalance and optimizing the spacing of heat transfer boreholes are key steps in maximizing the efficiency and reliability of GSHPs. the energy, economic, and environmental benefits of GSHPs further emphasize their potential for widespread implementation. With attention to technological advances and policies, GSHPs can be effectively utilized to promote sustainable development and environmental protection.

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE, introduces the background and purpose of the study. First, the current status of global and Chinese energy applications is introduced. Secondly, the current status of building energy in China and the current measures for using alternative energy sources are presented. Third, the current development status of geothermal energy as well as ground source heat pumps is introduced, and the Chinese government's policy of vigorously developing geothermal energy and the application of ground source heat pumps in China are presented. Finally, the research objectives and logical framework of this study are summarized.

In Chapter 2, LITERATURE REVIEW ON GROUND SOURCE HEAT PUMP SYSTEMS, The types of GSHP as well as the working principle and composition are introduced, and the current status of the application and development of ground source heat pumps in previous studies, the development process of the technology and its advantages are reviewed, while the problems and technical bottlenecks encountered in the application of the technology and the problems encountered in the application for cold regions are analyzed in the context of previous studies. The literature review is conducted for the most concerned heat balance problem and energy efficiency in cold regions, and the previous research methods and conclusions are introduced.

In Chapter 3, RESEARCH SUBJECTS AND METHODS, the basic situation of the research topic, various parameters of the building and the composition and various parameters of the ground source heat pump are introduced, as well as the working principle of the ground source heat pump using area compensation technology to achieve the cooling and heating load balance of the research topic. Secondly, we introduced the application scope and method of soil temperature

field modeling using CFD software to study the changes of soil temperature field during the long-term operation of the ground source heat pump system. Finally, the simulation method for ground source heat pump system performance study is introduced, and the use of TRNSYS software is described to establish the system operation performance model and the modules used in the model are explained in detail.

In Chapter 4, STUDY OF SOIL HEAT BALANCE OF GSHPS, Combined with the monitoring platform, the monitoring data of unit performance and subsurface soil temperature were studied and analyzed. Meanwhile, CFD software was used to simulate the effect of heat exchange holes on subsurface soil temperature under different spacing conditions after 30 years of system operation, and the optimization of heat exchange hole spacing in cold regions was proposed. This study provides first-hand real-time monitoring data of GSHP operation in cold regions, as well as temperature field variation data of subsurface soil at different depths for 8 consecutive years. The results show that the ground-source heat pump system maintains the thermal balance of subsurface soil temperature by regulating the equalization of cold and heat loads in the severe cold region. The practicality of ground source heat pumps in severe cold regions is further confirmed by simulation and experimental studies. Meanwhile, by analyzing the changes of soil temperature around the buried tube heat exchange well set with different heat exchange hole spacing, it is found that the difference of each spacing is small after long-term operation, so it is not necessary to pursue excessively to increase the heat exchange hole spacing to maintain the thermal balance of soil temperature field under the limited area of ground source heat pump project.

In Chapter 5, ENERGY EFFICIENCY ANALYSIS OF GSHPs, The energy efficiency of the ground source heat pump system is discussed in terms of both energy analysis and fire use analysis. The results of monitoring data for 8 years of system operation are analyzed, and the changes in the operational performance of the system after 30 years of operation are analyzed through simulation studies. Also, a fire analysis was performed for each energy-using unit in the system relative to the total energy use. The first part of the study focused on confirming the long-term stable operation of the ground source heat pump system. This analysis considered factors such as supply and return water temperature variations, flow rate variations, and average input power variations between the ground source side and the consumer. It was found that after 8 years of operation, the system maintained a stable performance with a high coefficient of performance (COP), indicating good energy savings. Even after 30 years of simulated operation, the system continued to operate efficiently. The primary energy efficiency was also calculated for both winter and summer conditions and showed that the ground source heat pump system has a higher energy efficiency compared to the conventional heating system. The system achieves a significant energy saving of 47.9%. Finally, the efficiency of the ground source heat pump system was analyzed, specifically examining the energy-using units. It was found that the lowest efficiencies occurred at the beginning of the main energy-using lines, resulting in significant heat losses. A comparison with a conventional air-cooled heat pump + central heating system shows that the soil source heat pump system is more efficient. Overall, the use of area compensation techniques effectively ensures the stability and energy efficiency ground source heat pump systems in long-term operation.

In Chapter 6, ECONOMIC AND ENVIRONMENTAL ANALYSIS OF GSHPS, The adaptability of ground source heat pump in severe cold regions was analyzed in terms of both environmental and economic benefits. In terms of economic analysis, static and dynamic analysis methods were used to analyze the soil source heat pump system and conventional air-cooled heat pump + central heating system, including simple payback period, return on investment, present value of cost, annual value of cost and dynamic payback period. The results show that the soil source heat pump system is very economical; moreover, the present value of cost and annual value of cost of the soil source heat pump system are relatively low; its dynamic payback period is 4.8 years, i.e., the incremental cost can be recovered after 4.8 years. In terms of coal saving, calculated from the data of the system's long-term operation for 8 years, compared with the energy saving of 388.78 tons of standard coal for conventional boiler room heating and 250.8 tons of standard coal for conventional air conditioning and cooling, the system achieves a total energy saving of 639.58 tons of standard coal for 8 years of operation. In terms of environmental benefits, the system has been operating for 8 years and has reduced carbon dioxide emission by 1579.75 tons, sulfur dioxide emission by 12.79 tons and soot emission by 6.39 tons, which shows that GSHP can reduce a large amount of coal energy and emission of harmful substances such as carbon dioxide in long-term operation. Therefore, it is important to promote the use of ground source heat pump system in cold regions, which is conducive to changing the traditional energy structure of China and reducing the use of energy sources such as coal.

In Chapter 7, CONCLUSION AND PROSPECT, a critical summary of each chapter was concluded.

***Keywords*:** Clean Energy; Carbon Neutral; simulation model; GSHPs

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Chapter 1

RESEARCH BACKGROUND AND PURPOSE

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1.1 Research background

1.1.1 Status of the world energy

Energy is an important material basis for human survival and development[1, 2]. It has been proved that to achieve a high level of material civilization, it is necessary to vigorously promote the steady and rapid development of social productivity[3], which is highly dependent on modern agriculture, industry, transportation and logistics systems as well as modern living facilities and service systems, and the perfection and operation of these systems are inseparable from energy[4, 5]. In modern society, although the proportion of energy used for food to sustain people's life in the total energy consumption has decreased significantly, the proportion of energy consumption in production, living and transportation services is increasing year by year[6].

In recent years, with the changes in the world landscape, the issue of energy development has always been closely related to international politics, international security and the world economic situation, and has become the object of great attention by the international community[7-9]. As the importance of energy use has increased, the environmental problems caused by energy use have also begun to gain attention, even inspiring many scholars to keep exploring to discover its causative factors[10-12].

With the oil crisis, mankind has clearly recognized the importance of environmental protection and energy conservation in social development[13-15]. The BP World Energy Statistics Yearbook 2022 shows that global primary energy consumption rebounded sharply in 2021, up 5.8% year-on-year, driven by economic recovery, exceeding 2019 levels by 1.3%. Figure 1-1/1-2 shows between 2019 and 2021, renewable energy increased by over 8 EJ. Consumption of fossil fuels was broadly unchanged. Fossil fuels accounted for 82% of primary energy use last year, down from 83% in 2019 and 85% five years ago. Primary energy grew by 31 EJ in 2021, the largest increase in history and more than reversing the sharp decline seen in 2020. Primary energy in 2021 was 8 EJ above 2019 levels. The increase in primary energy in 2021 was driven by emerging economies, which increased by 13 EJ, with China expanding by 10 EJ. Since 2019, primary energy consumption in emerging economies increased by 15 EJ, largely reflecting growth in China (13 EJ). In contrast, energy demand in developed economies in 2021 was 8 EJ below 2019 levels. The increase in primary energy between 2019 and 2021 was entirely driven by renewable energy sources. The level of fossil fuel energy consumption was unchanged between 2019 and 2021, with lower oil demand (-8 EJ) offset by higher natural gas (5 EJ) and coal (3 EJ) consumption[16].

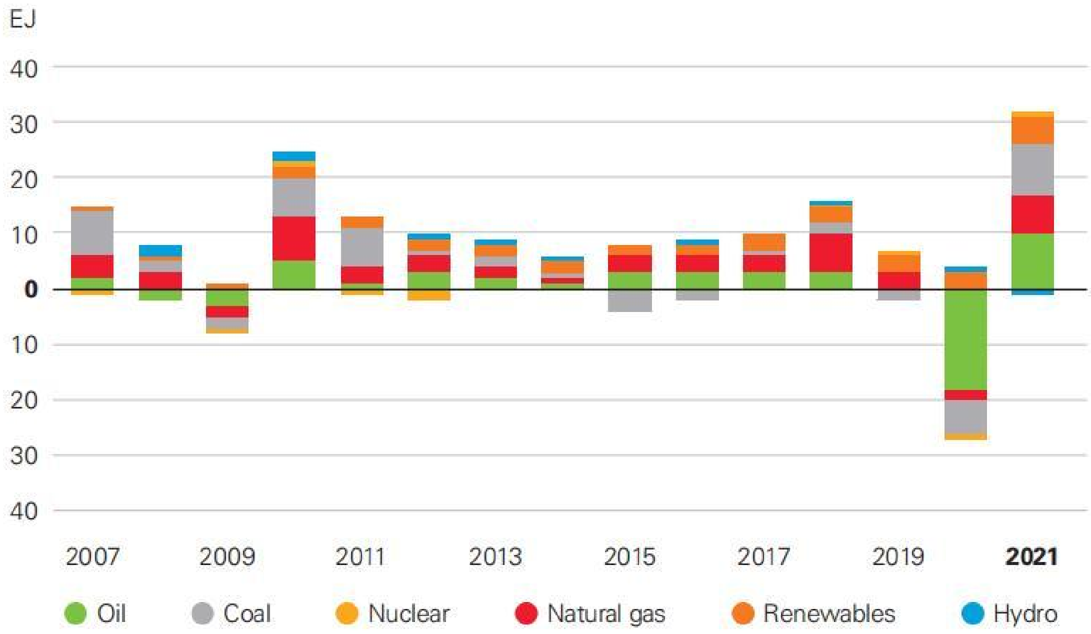

Fig 1-1 Change in primary energy by fuel[16]

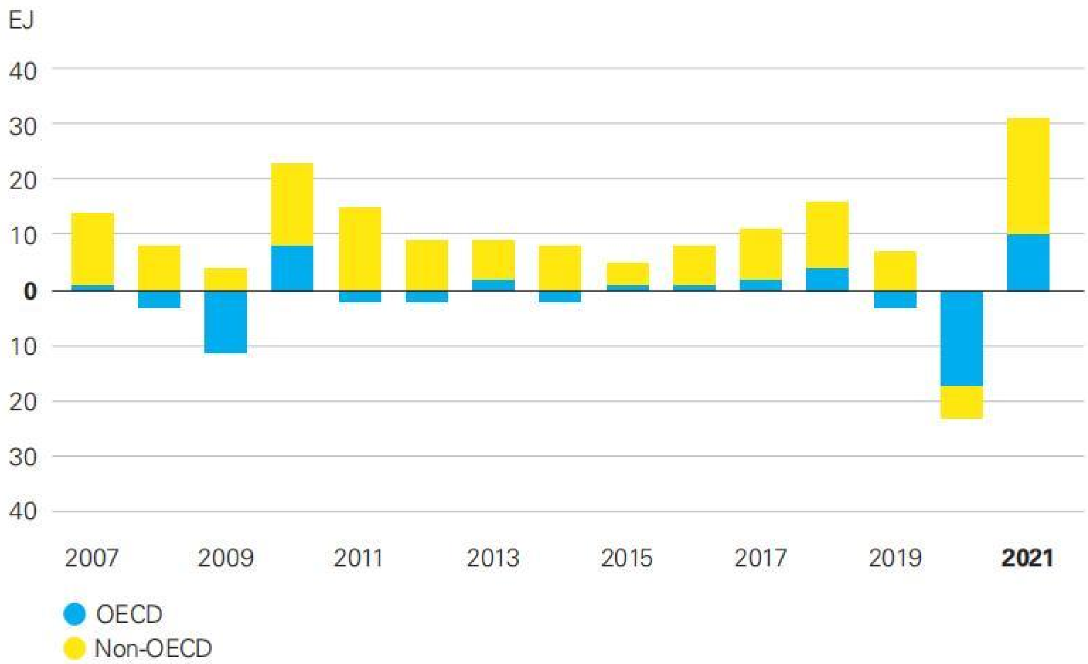

Fig 1-2 Change in primary energy by geography[16]

Fig 1-3 shows North America includes Canada, Mexico, the United States primary energy consumption accounted for 19.1% of the global total, South and Central America includes Brazil, Argentina, Colombia, Peru and other 11 countries and regions primary energy consumption accounted for 4.8%, Europe includes the United Kingdom, Italy, Germany, Turkey and other 34 countries and regions primary energy consumption accounted for 13.8%, the CIS includes Russia, The CIS includes Russia, Azerbaijan, Belarus, Kazakhstan, Turkmenistan, Uzbekistan and other countries and regions primary energy consumption accounted for 6.8%, the Middle East region including Iran, Iraq, Israel and other 9 countries and regions primary energy consumption accounted for 6.4%, Africa region including South Africa, Morocco, Central Africa, East Africa, West Africa and other countries and regions primary energy consumption accounted for 3.4%, the Asia-Pacific region including Australia, Japan, Singapore, India, China and other countries and regions primary energy consumption accounted for 45.8%.

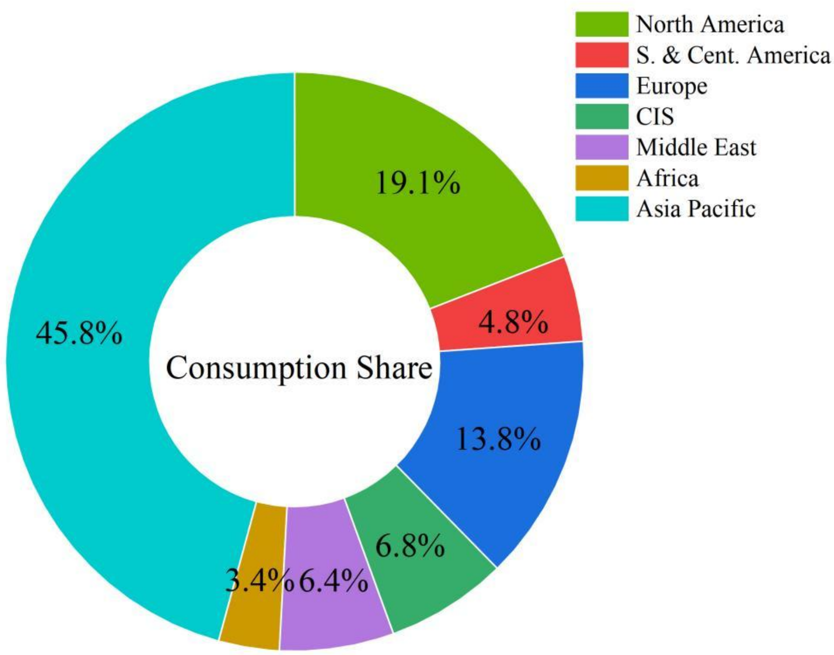

Fig 1-3 World primary energy consumption share

Emissions from energy rebounded strongly in 2021 back to around 2019 levels. The sharp rebound in emissions in 2021 was explained by economic growth. As economic activity recovered from lock downs and other COVID-19 related measures, energy consumption increased sharply. Carbon intensity and, to lesser extent, energy intensity were largely unchanged in 2021[16]. Global carbon emissions have also increased by 5.7%, and net zero emissions commitments have not yet fully translated into real progress. Fig. 1-4 shows North America accounts for 16.5% of global CO2 emissions from energy sources, South and Central America for 3.6%, Europe for

11.2%, CIS for 6.3%, the Middle East for 6.2%, Africa for 3.8%, and Asia Pacific for emissions in the Asia-Pacific region accounted for 52.3%.

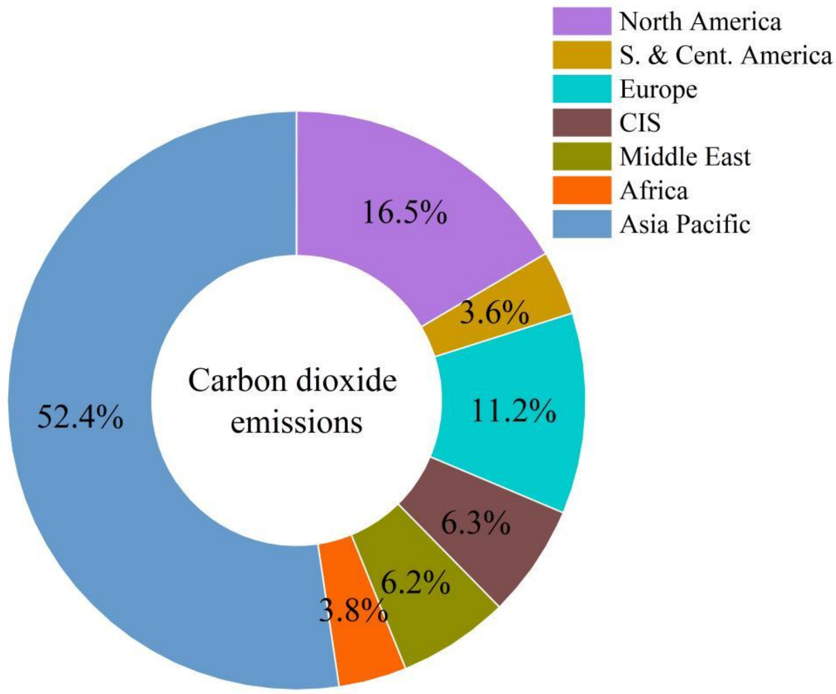

Fig 1-4 Carbon dioxide emissions from energy

Encouragingly, renewable energy, led by wind and solar, continues to grow strongly, with renewable energy generation increasing by nearly 17% in 2021[16]. global primary energy consumption increases by nearly 6% year-on-year in 2021, reversing the sharp decline in energy consumption caused by the 2020 epidemic and exceeding the 2019 level by more than 1%[17]. In incremental terms, global primary energy consumption increases by 31 exajoules (EJ) year over year in 2021, the largest increase on record, and in terms of energy type, fossil energy accounts for 82% of primary energy consumption in 2021, with fossil energy consumption levels remaining unchanged over this period, with lower oil demand (down 8 EJ) offset by higher natural gas (up 5 EJ) and coal (up 3 EJ Between 2019 and 2021, the growth in primary energy consumption is entirely driven by renewable energy sources. Renewables share in power generation reached almost 13% in 2021, higher than the share of nuclear energy (9.8%)[16].

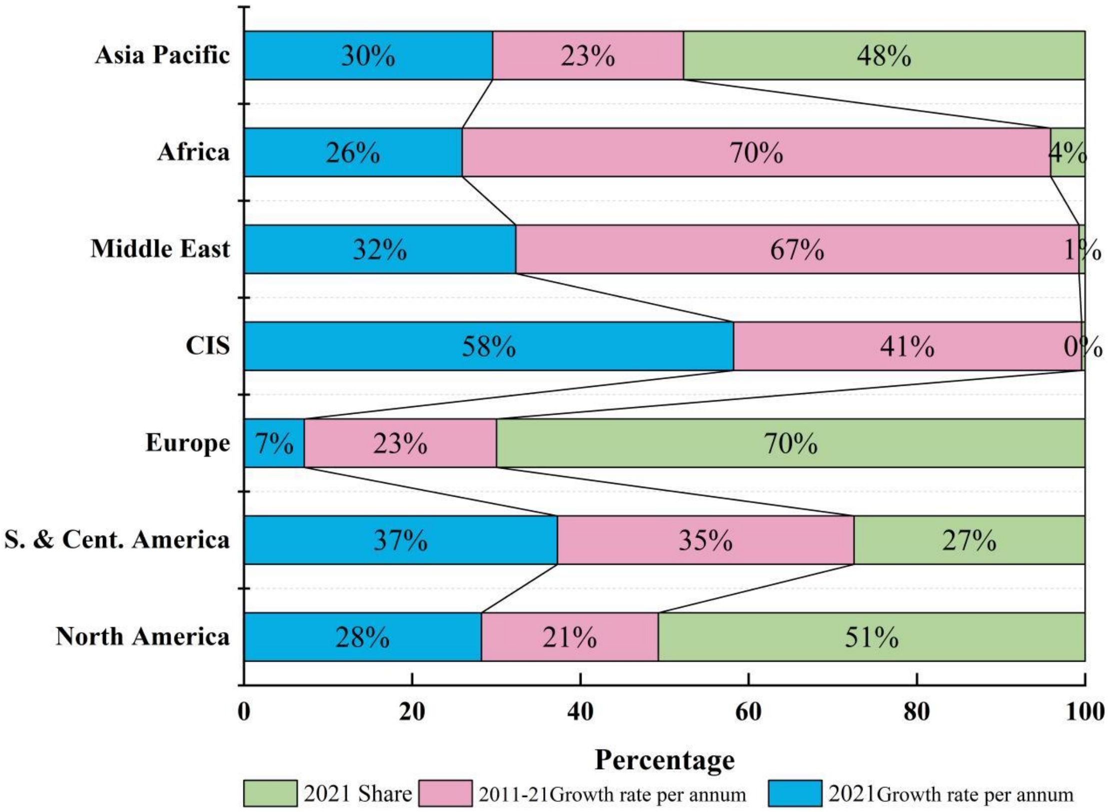

Fig 1-5 Renewable energy consumption

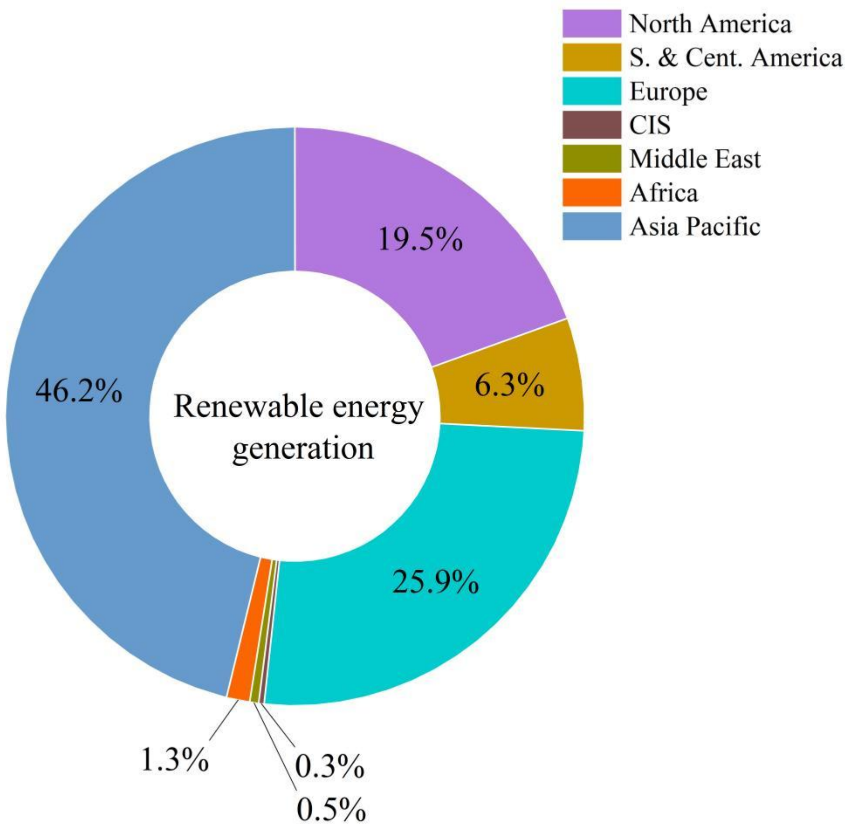

Fig 1-6 Renewable energy generation

1.1.2 Status of energy in China

(1) Energy structure

In the energy sector, China's international cooperation is also expanding, from the initial focus on oil and natural gas to new energy sources such as coal, electricity, wind energy, biomass fuel and nuclear energy[18, 19]. China's state-owned oil companies, undertaking and fulfilling the important mission of comprehensive political, economic and social development, while ensuring national energy security, also focus on this strategic goal of building a comprehensive international energy company[20], actively implement three major strategies of resources, markets and internationalization, and have made great achievements in pooling resources and opening up domestic and foreign markets[21]. As a major energy-consuming country, China needs to change its economic development mode, adhere to the new industrialization path, and vigorously develop new energy industries to achieve sustainable economic and social development in order to ease the contradiction between economic development, environmental protection and energy consumption[22-24].

The BP World Energy Statistics Yearbook 2022[16] shows that China surpassed Japan as the world largest LNG importer and accounted for close to 60% of global LNG demand growth in 2021. According to China Statistical Yearbook 2022, Fig 1-7 shows China's total energy production and consumption increased year by year from 2011 to 2021, with total production increasing by 92822 million tons of standard coal and total consumption increasing by 136957 million tons of standard coal. Total consumption is greater than total domestic production, and the share of energy imports is increasing year by year.

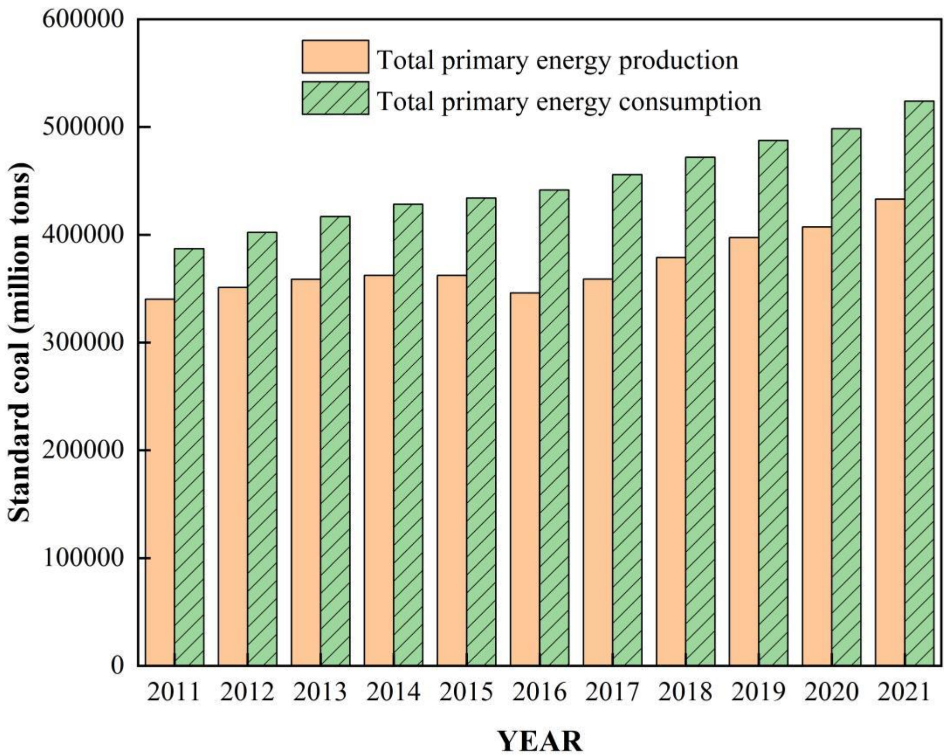

Fig 1-7 Total primary energy production and consumption in China

China has recently paid more attention to the development of new energy technologies. China's current energy mix is irrational, with a low proportion of clean energy sources like new energy, a large proportion of coal, high external dependence on oil, low per capita energy share, and low energy utilization[24]. China is facing the serious challenge of limited fossil fuel resources and higher environmental protection requirements. In order to reach the level of medium developed countries by 2050, China has to choose the direction of developing new advantageous industries. The development of new energy sources is currently the only way to solve the problem simultaneously[23, 25]. China remained the main driver of solar and wind capacity growth last year, accounting for about 36% and 40% of the global capacity additions, respectively. Hydroelectricity generation decreased by around 1.4% in 2021, the first fall since 2015. In contrast, nuclear generation increased by 4.2% , the strongest increase since 2004.

Fig 1-8 shows Composition of primary energy production in China, From 2011-2021, the structure of China's energy production changed, with the share of production from raw coal and crude oil decreasing year by year, by 10.8% and 1.9%, respectively, and the share of production from natural gas and primary electricity increasing year by year, by 2% and 9.1%, respectively. However, raw coal feedstock still dominates, accounting for 67% in 2021.

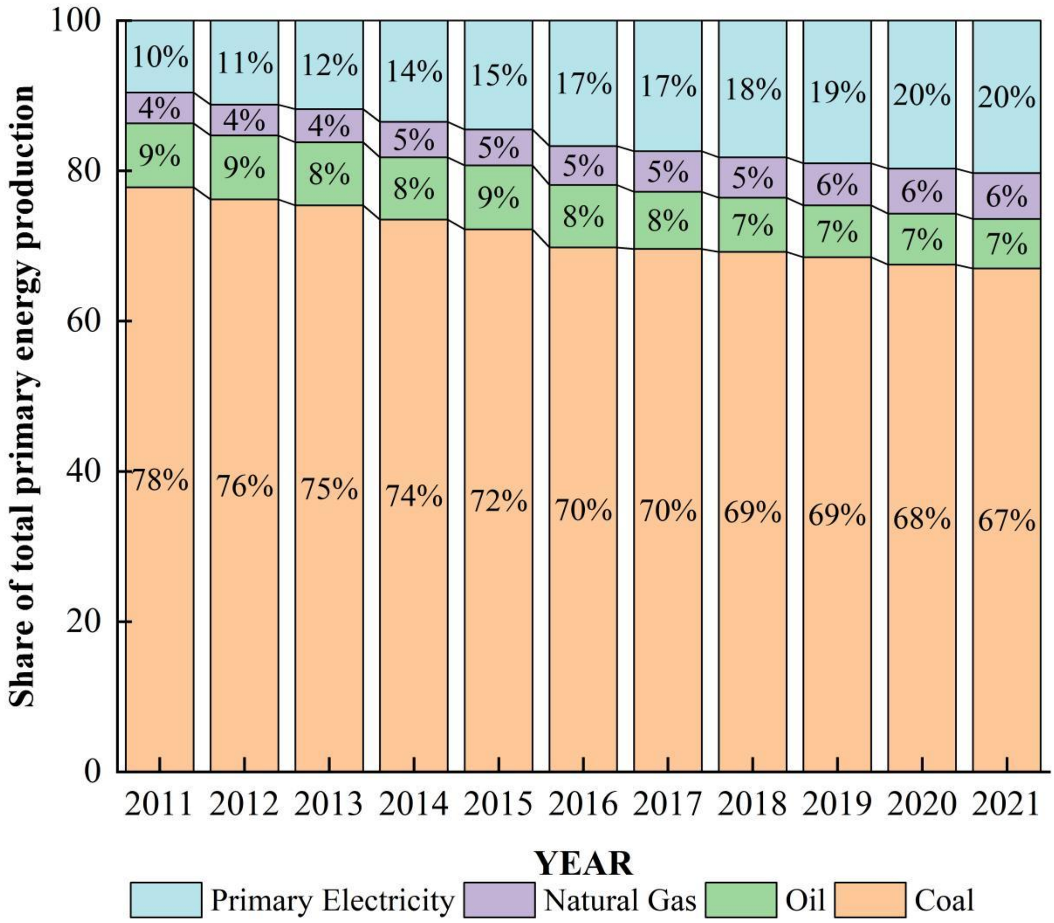

Fig 1-8 Composition of primary energy production in China

According to China's National Bureau of Statistics data, as shown in Figure 1-9, emissions of major air pollutants have been decreasing year by year, with sulfur dioxide emissions at 2,747,800 tons in 2021, down 87.61% compared to 2011; nitrogen oxide emissions at 9,726,500 tons, down 59.54% compared to 2011; particulate matter emissions at 5,376,000 tons, compared to 2011 Compared with 2011, particulate matter emissions decreased by 57.96%. With the reduction of primary energy use, the emissions of major pollutants in the air were relatively reduced.

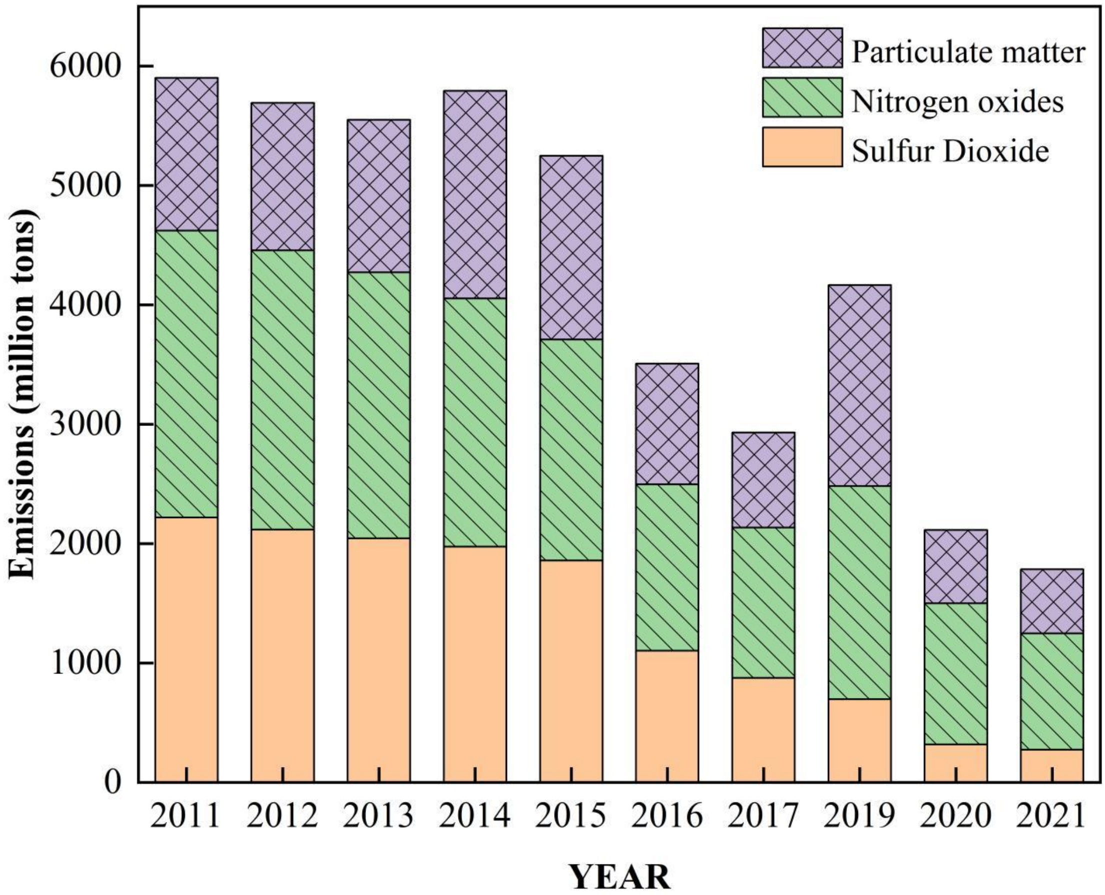

Fig 1-9 Emissions of air pollutants in China

(2) Electric power energy

With the development and use of electric energy, electric energy is widely used as a supply method in various regions of China[22, 26], Fig 1-10 shows China's energy mix changes from 2011-2021, with the share of coal consumption decreasing by 14.2%, the share of oil consumption increasing by 1.7%, the share of natural gas consumption increasing by 4.3%, and the share of primary electricity consumption increasing by 8.2%. According to the data of China Statistical Yearbook-2022, as shown in Table 1-1, China's electricity production has increased year by year since 1990-2020, with thermal power generation accounting for 68.7%, hydroelectric power generation accounting for 17.5%, and nuclear power and wind power increasing year by year in 2020. Table 1-2 shows that the installed power generation capacity is increasing year by year, and the total installed power generation capacity in 2021 is 237,777,000 kilowatts, which is 55.3% higher than that in 2011, including 40.7% increase in thermal power generation, 40.4% increase in hydropower, 76.4% increase in nuclear power, 85.9% increase in wind power, and 99.3% increase in solar power. As shown in Fig 1-11, in 2021, China's installed thermal power generation capacity is 129739 million kilowatts, accounting for 54.6% of the total annual installed power generation capacity; installed hydroelectric power generation capacity is 39094 million kilowatts, accounting for 16.4% of the total annual installed power generation capacity; installed nuclear power generation capacity is 5326 million kilowatts, accounting for 2.2% of the total annual installed power generation capacity; installed wind power generation capacity is The installed capacity of wind power generation was 32871 million kilowatts, accounting for 13.8% of the total annual installed power generation capacity; the installed capacity of solar power generation was 30654 million kilowatts, accounting for 12.9% of the total annual installed power generation capacity. This also shows that China's electric energy is still dominated by thermal power generation, while nuclear power, wind power, solar power and other power generation methods are being vigorously promoted[27].

Table 1-1 Total electricity and energy production in China and its composition

Electricity Category	1990	1995	2000	2005	2010	2015	2018	2019	2020
Production volume (million kilowatts)	6212	10077	13556	25003	42072	58146	71661	75034	77791
Hydroelectric (million kilowatts)	1267	1906	2224	3970	7222	11303	12318	13044	13552
Thermal Power (million kilowatts)	4945	8043	11142	20473	33319	42842	50963	52202	53303
Nuclear Power (million kilowatts)		128	167	531	739	1708	2944	3484	3663
Wind Power (million kilowatts)					446	1858	3660	4060	4665

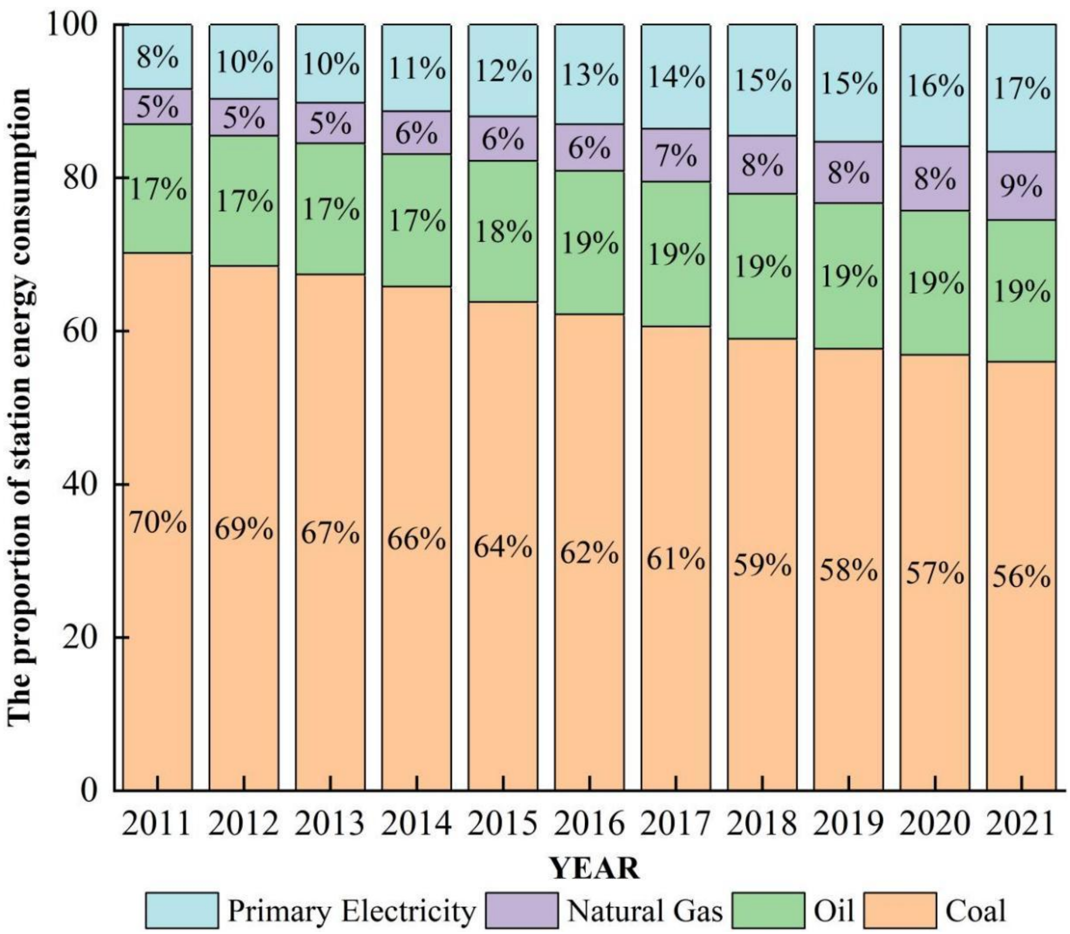

Fig 1-10 Weight share of energy consumption in China

Table 1-2 Installed Power Generation Capacity in China

YEAR	Installed power generation capacity (million kilowatts)	Thermal Power (million kilowatts)	Hydroelectric (million kilowatts)	Nuclear Power (million kilowatts)	Wind Power (million kilowatts)	Solar Power (million kilowatts)
2011	106253	76834	23298	1257	4623	212
2012	114676	81968	24947	1257	6142	341
2013	125768	87009	28044	1466	7652	1589
2014	137887	93232	30486	2008	9657	2486
2015	152527	100554	31954	2717	13075	4218
2016	165051	106094	33207	3364	14747	7631
2017	177708	110495	34359	3582	16325	12942
2018	190012	114408	35259	4466	18427	17433
2019	201006	118957	35804	4874	20915	20418
2020	220204	124624	37028	4989	28165	25356
2021	237777	129739	39094	5326	32871	30654

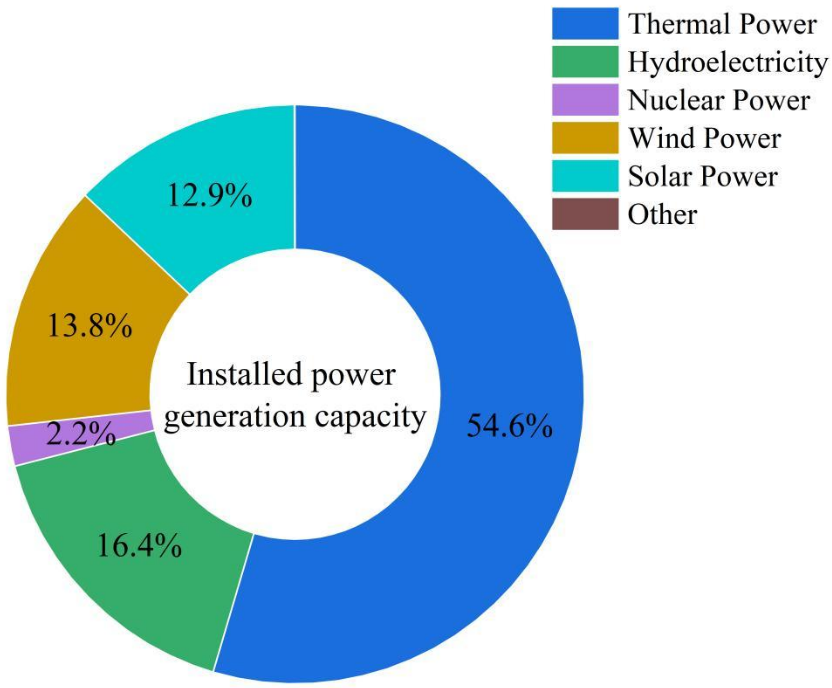

Fig 1-11 Share of installed power generation capacity in 2021

According to the data of the National Bureau of Statistics of China, as shown in Table 1-3, since 1995-2021, the electricity consumption of China's regions has increased year by year, with total electricity consumption of 10105 Billion kWh in 1995, 1,3605 Billion kWh in 2000, 2,4759 Billion kWh in 2005, 4,9977 Billion kWh in 2010, 4,9977 Billion kWh in 2015, total The total electricity consumption in 2015 was 56,935 Billion kWh, 7,5214 Billion kWh in 2020 and 8,3316 Billion kWh in 2021. Among them, Northeast China including Jilin, Liaoning and Heilongjiang will consume 3682 Billion kWh of electricity in 2021; North China including Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia will consume 13074 Billion kWh of electricity in 2021; East China including Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi and Shandong will consume 2,9163 Billion kWh of electricity in 2021; Central China including Henan, The electricity consumption in Central China, including Henan, Hubei and Hunan, will be 8274 Billion kWh in 2021; the electricity consumption in South China, including Guangdong, Guangxi and Hainan, will be 1051 Billion kWh in 2021; the electricity consumption in Southwest China, including Sichuan, Yunnan, Guizhou, Tibet and Chongqing, will be 58599 Billion kWh in 2021; the electricity consumption in Northwest China, including Ningxia, Xinjiang, Qinghai, Shaanxi and Gansu, will be 9188 Billion kWh in 2021. Beijing, Shanghai, Tianjin, Chongqing, the four municipalities directly under the Central Government and coastal areas, densely populated areas of electricity consumption is larger, less economically developed areas of electricity consumption than economically developed areas[28].

Table 1-3 Installed Power Generation Capacity in China

Region	Electricity consumption (Billion kWh)						
	1995	2000	2005	2010	2015	2020	2021
Beijing	262	384	571	810	953	1140	1233
Tianjin	179	234	385	646	801	875	982
Hebei	603	809	1502	2692	3176	3934	4294
Shanxi	399	502	946	1460	1737	2342	2608
Inner Mongolia	187	254	668	1537	2543	3900	3957
Liaoning	623	749	1111	1715	1985	2423	2576
Jilin	268	291	378	577	652	805	843
Heilongjiang	409	442	556	748	869	1014	1089
shanghai	403	559	922	1296	1406	1576	1750
Jiangsu	685	971	2193	3864	5115	6374	7101
Zhejiang	440	738	1642	2821	3554	4830	5514
Anhui	289	339	582	1078	1640	2428	2715
Fujian	261	402	757	1315	1852	2483	2837
Jiangxi	181	208	392	701	1087	1627	1863
Shandong	741	1001	1912	3298	5117	6940	7383
Henan	571	719	1353	2354	2880	3392	3647
Hubei	415	503	789	1330	1665	2144	2472
Hunan	375	406	674	1172	1448	1929	2155
Guangdong	788	1335	2674	4060	5311	6926	7867
Guangxi	221	314	510	993	1334	2029	2238
Hainan	32	38	82	159	272	363	405
Chongqing	0	308	348	626	875	1186	1341
Sichuan	583	521	943	1549	1992	2865	3275
Guizhou	204	288	487	835	1174	1586	1743
Yunnan	224	274	557	1004	1439	2025	2139
Tibet	0	0	0	20	41	82	101
Shaanxi	240	293	516	859	1222	1741	2217
Gansu	241	295	489	804	1099	1376	1495
Qinghai	69	109	207	465	658	742	858
Ningxia	92	136	303	547	878	1038	1158
Xinjiang	120	183	310	662	2160	3099	3460

1.1.3 Status of building energy in China

While China's energy consumption continues to shift to cleaner[29], low-carbon fuels, the overall trend in China's total energy consumption continues to grow and the total amount of energy consumed remains large[30-32]. Energy consumption is mainly composed of industrial energy consumption, transportation energy consumption and building energy consumption[33-35]. Among them, building energy consumption includes energy used in the production of building materials, energy used in the transportation of building materials, energy used in the process of building construction and maintenance, and building operation energy used in the process of building use[36, 37]. Building operation energy consumption is the main concern in the task of building energy saving, which generally refers to the energy consumption of building operation, i.e. the energy consumption of lighting, heating, air conditioning and all kinds of electrical appliances used in the building, which will always occur along with the process of using the building[38].

China is a large building country, building energy consumption accounts for nearly 30% of the total energy consumption of society[39, 40], building energy consumption has become the second largest energy consumption industry after industrial energy consumption, and the building area is still growing at an alarming rate, with 1.8 billion to 2 billion square meters of new building area every year[41], which is equivalent to the sum of the building area of other countries in the world, while the energy consumption per unit of building area is equivalent to 2~3 times that of developed countries[42, 43]. If the energy consumption of buildings is not controlled, the proportion of energy consumption in buildings to social energy consumption may continue to grow, and energy saving in buildings involves all aspects of society, and is a social action closely related to engineering technology, cultural philosophy, lifestyle, social equity and other issues[44]. Therefore, the share of building energy consumption is bound to climb year by year[45]. According to China Statistical Yearbook 2022, the share of building energy consumption in China is rising year by year[46].

As shown in Table 1-4 Building energy consumption in 2020 was 93.2 million tons of standard coal, an increase of 86.9% compared to 1990, 76.3% compared to 2000, and 40.6% compared to 2010. Table 1-5 shows that in 2020, China's total building energy consumption will be 93.2 million tons of standard coal, of which, coal consumption will be 6.39 million tons of standard coal, accounting for 6.8% of the total building energy consumption; coke consumption will be 40,000 tons of standard coal, accounting for 0.04% of the total building energy consumption; gasoline consumption will be 5.08 million tons of standard coal, accounting for 5.4% of the total building energy consumption; kerosene consumption will be 110,000 tons of standard coal, accounting for 0.1% of the total building energy consumption 0.1% of the total energy consumption of buildings; diesel consumes 5.04 million tons of standard coal, accounting for 5.4% of the total energy consumption of buildings; fuel oil consumes 410,000 tons of standard coal, accounting for 0.4% of the total energy consumption of buildings; natural gas consumes 300 million cubic meters, equivalent to 399,000 tons of standard coal, accounting for 0.43% of the total energy consumption of buildings; electricity consumes 101.1 billion kilowatt hours, equivalent to 12,419,300 tons of standard coal, accounting for 13.3% of the total energy consumption of buildings. of the total building energy consumption, accounting for 13.3%[47]. The data show that the proportion of electricity consumption in the total energy consumption of buildings is greater than that of coal and other consumption.

Table 1-4 Building energy consumption in China

YEAR	1990	1995	2000	2005	2010	2015	2018	2019	2020
Building energy consumption (million tons of standard coal)	1213	1335	2207	3486	5533	7545	8685	9142	9320

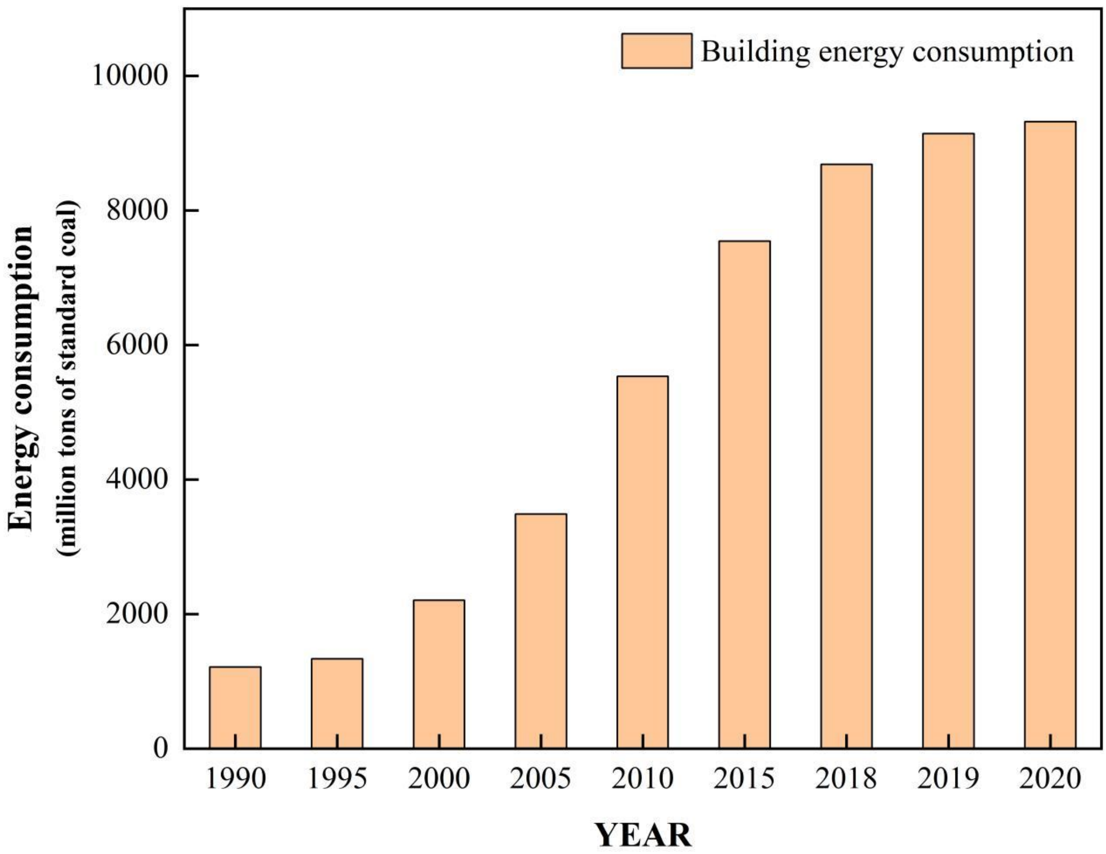

Fig 1-12 Building energy consumption in China

Table 1-5 Building energy consumption classification in 2020

Category	Coal	Coke	Gasoline	Kerosene	Diesel	Fuel Oil	Natural Gas	Electric Power
Energy consumption (million tons of standard coal)	639	4	508	11	504	41	39.9	1241.93

The Chinese government's Plan for Clean Winter Heating in Northern Areas (2017-2021) aims to address the low proportion of clean heating in the northern regions, particularly in areas where a significant amount of loose coal is used during the winter[48]. The promotion of clean heating is crucial for ensuring the warmth of the population in the northern regions during winter and reducing the occurrence of hazy days. It is considered part of the energy production and consumption revolution and the rural lifestyle revolution[49].

The plan sets specific targets for clean heating implementation. By 2019, the clean heating rate in northern areas is expected to reach 50%, resulting in the replacement of 74 million tons of loose coal, including coal used in inefficient small boilers. By 2021, the clean heating rate should reach 70%, leading to the replacement of 1.5 million tons of scattered coal, including coal used in inefficient small boilers. Additionally, 150 million tons of bulk coal, including coal used in inefficient small boilers, is targeted for replacement by 2021.

The plan encourages the adoption of electric heating in regions with abundant renewable energy resources, such as Xinjiang, Gansu, Inner Mongolia, Hebei, Liaoning, Jilin, Heilongjiang, and other areas. It promotes the utilization of surplus wind power during low periods and encourages the construction of electric heating facilities with heat storage capabilities[50, 51]. The goal is to increase the consumption of renewable energy sources like wind power and photovoltaic power in electric heating systems[52].

By 2021, the total area covered by electric heating, including heat pumps, is projected to reach 1.5 billion square meters. This includes 700 million square meters of decentralized electric heating, 300 million square meters of electric boiler heating, and 500 million square meters of heat pump heating. Urban areas will contribute 1 billion square meters to electric heating, while rural areas will account for 500 million square meters. The implementation of electric heating is expected to result in an additional electricity consumption of 110 billion kWh[53].

Furthermore, the plan emphasizes the vigorous development of shallow geothermal energy for heating purposes. This involves accelerating the promotion and application of various shallow geothermal energy utilization technologies. The approach is based on utilizing local conditions, promoting intensive development, strengthening supervision, and prioritizing environmental protection[54]. The aim is to economically and efficiently replace bulk coal heating with shallow geothermal energy[55].

Overall, the Plan for Clean Winter Heating in Northern Areas (2017-2021) in China focuses on transitioning from coal-based heating systems to cleaner alternatives such as electric heating and shallow geothermal energy[56, 57]. This shift is driven by the need to reduce pollution, improve air quality, and enhance the living conditions of the population in the northern regions[58, 59].

Table 1-6 Electric heating development route and applicable conditions

Electric heating method	Applicable conditions
Decentralized electric heating	Suitable for non-continuous heating in schools, troops, office buildings and other places, also suitable for old urban areas, urban-rural areas, rural areas or areas with high ecological requirements that cannot be covered by the centralized heating network or gas pipeline network. Residential houses in areas with high ecological requirements.

Electric boiler heating	It should be equipped with heat storage facilities, suitable for renewable energy consumption pressure, abandoned wind, abandoned light It can be used for single building or small district heating in areas with serious problems of wind and light abandonment and large demand for grid peaking.
Air source heat pumps	It has certain requirements for the minimum outdoor temperature in winter (generally higher than -5 ℃), and is suitable as a centralized It is suitable as a supplement to central heating, undertaking single building or small district heating (cooling), and can also be used for sub-family heating.
Water source heat pumps	Applicable to areas with suitable water quantity, water temperature, water quality and other conditions. Priority use of urban sewage Resources, the development of sewage source heat pump, for seawater or lake water resources rich areas according to the water temperature and other conditions appropriate development. Development. For buildings with cooling and heating needs, it can take into account summer cooling. It is suitable as a supplement to centralized heat supply, undertaking single The heating (cooling) of a single building or a small district is suitable.
Ground source heat pumps	Suitable for good geological conditions, basic balance between winter heating and summer cooling, easy to bury pipes It is suitable for single building or small district heating (cooling) in the building or area.

In July 2022, China's Development and Reform Commission's latest "14th Five-Year Plan" for the implementation of new urbanization emphasized the promotion of the renewal and renovation of pipeline networks and the construction of underground corridors[48]. The "14th Five-Year Plan" issued by the Ministry of Housing and Construction aims to complete the energy-saving renovation of more than 100 million square meters of existing residential buildings nationwide by 2025. According to the policy development plan, the future energy consumption of urban heating units will be reduced, the promotion of industrial waste heat centralized heating, accelerate the construction and renovation of heating pipeline network and promote clean energy heating will be the focus of development[60]. From the urban heating development plans of various provinces and cities, the renewable energy, clean heating area has an indicative requirement is Beijing and Shenyang. Liaoning in clean heating project investment "fourteen five" target is 41 billion yuan; Shandong to industrial waste heat heating transformation area of 500 million square meters; Shaanxi, Guizhou planning in 2025 geothermal heating were raised to 70 million square meters and 25 million square meters; Inner Mongolia planning 2025 without electricity unit energy-saving transformation 20 million kilowatts, Anhui planning green building area by 2025 accounted for more than 30%. Other regions also have plans for urban heating, but most of them are indicators of green floor space and coal power unit renovation[61].

Table 1-7 Urban heating development plans for some Chinese provinces and cities during the 14th Five-Year Plan

Province and City	Heating Policy
Heilongjiang	Vigorously promote the transformation of coal power units to reduce energy consumption, flexibility transformation, heat supply transformation, three changes in the linkage, to meet the demand for electricity and heat in principle, the region is not in the scale of new coal power.
Jilin	By 2025, the proportion of clean heating such as ultra-low emission hotspots, large coal-fired boiler houses with up to standard emissions and clean energy will increase to more than 90%.
Liaoning	The 14th Five-Year Plan period to promote clean energy projects investment of 41 billion yuan.
Inner Mongolia	Continuously expand the centralized heating area of cogeneration, promote the centralized heating of industrial waste heat, scientific and orderly promote the dual replacement of bulk coal, and by 2025, complete the energy-saving transformation of coal power units 20 million kilowatts, flexibility transformation of 30 million kilowatts.
Beijing	By 2025, the renewable energy heating area will reach more than 10%, and the energy consumption per unit of floor space for heating will drop by about 10%.
Shandong	By 2025, a number of industrial waste heat utilization demonstration projects will be implemented, and the industrial waste heat heating transformation area will strive to reach 500 million square meters.
Shaanxi	Geothermal energy heating area increased to 70 million square meters by 2025.

1.1.4 Status of electric heating technology in cold regions of China

With the deepening of human understanding of the laws of economic and social development, building an ecologically wise civilization has become an inevitable choice for sustainable economic, social and environmental development[62-65]. Currently, the world's energy structure is accelerating toward low-carbon and non-carbon development[66]. The development of clean, low-emission new and renewable energy has become the global trend of energy transformation[67]. The large-scale development and utilization of clean energy, especially new energy generation, will replace coal, oil and other terminal fossil energy sources, thus significantly increasing the proportion of electric energy in terminal energy consumption, which will become the future energy development trend[68, 69]. The clean heating transformation of electric coal will determine the clean heating method in cold areas in the next 10 years, solving problems such as electricity consumption and environmental protection[70, 71]. From the national heating situation, electric heating technology is a major trend[72]. The in-depth application of electric heating technology is a major project to promote the coordinated development of people's livelihood projects and environmental protection in Jilin Province, and is committed to fully serve the major needs of clean heating in Jilin Province[73]. Promoting clean heating throughout the province can effectively solve the problem of excess electricity, make full use of clean energy and avoid abandoning light[74]. At the same time, under the guidance of the concept of sustainable development, through technological innovation, institutional innovation, industrial regionalization, new energy development and other means to minimize the consumption of coal, oil and other high-carbon energy, reduce greenhouse gas emissions, the formation of economic and social development and ecological environment. A win-win economic development model for protection[75].

Since the development of China's cities has long been carried out in a crude economic growth mode, relying mainly on increased investment and material inputs[76]. relying primarily on increased investment and material inputs, consumption of energy and other resources has also grown rapidly[77]. The excessive consumption of resources has made and maintained sustainable urban development unsustainable. And economic growth is facing difficulties[78]. At the same time, air pollution caused by coal-fired boilers for heating in cold areas is also a growing concern[79]. Driven by these two reasons, electric heating technology has been developing rapidly in China in recent years. Taking Jilin Province, a cold region in China, as an example, the types of electric heating used in Jilin Province are mainly divided into centralized electric heating systems and decentralized electric heating systems. At present, electric heating in Jilin Province is mainly divided into centralized electric heating system and decentralized electric heating system. Centralized electric heating system mainly refers to water storage type electric boiler heating system and solid storage type electric boiler heating system[80, 81].Electric heating Pump heating system; decentralized electric heating system mainly includes heating cable heating system, electric heating film heating system, heating floor heating system. Membrane heating system, heating floor heating system, small floor or wall-mounted electric heater, development of different electric heating technologies to promote ecological wisdom city operation Safer, more efficient, greener and more harmonious goals to achieve urban ecological civilization[82].

(1) Analysis of electric heating technology

Modern cities are not only low-carbon cities with zero emissions, but also smart cities based on modern technology. The construction of smart city promotes the evolution of resource-depleted and environment-damaging real economy to resource-saving and environment-friendly ecological economy, and promotes the rigid production of traditional production methods from product-based to functional, chain-based to network-based, nature-based to knowledge-based, and factory-based to park-based[83]. Flexible production, attrition to efficiency, and occupational livelihood to eco-friendly circular economy.

Clean heating technology in Jilin Province is mainly divided into natural gas heating and electric heating. Natural gas heating is limited by the supply of natural gas, so electric heating has become the main trend of clean heating. The advantages of electric heating technology are reflected in many aspects. Generally speaking, it can be summarized into three parts: simple operation method, low cost, good heating effect, energy saving and environmental protection without pollution. At present, there are mainly the following categories of electric heating technologies [84].

Table 1-8 Advantages and disadvantages of different electric heating

Devices	Advantages	Disavantages
Air source heat pump/ Hot air blower	Lower price and abundant supply	EER is affected by ambient temperature,loud noise,easy to generate static electricty
Direct heating/ Regenerative electric boiler	Evading the investment in coal pollutoin, lower cost	pipeline leaks and post-maintenance issues
Direct heating/Regenerative heater	Fast heating. Save idle energy	Low quality,3-5 years' service life,high surface temperature,security risks
Other auxiliary heating facilities	Low energy consumption, low cost,high effciency	poor heating effect, high surface temperature, security risks

Electric heating mainly uses heating cables, electric boilers, direct electric heating electric heaters and heat pump products as heating equipment. Technologies such as heating cables, electric heating film and electric boilers directly convert high-grade electrical energy into low-grade thermal energy, which will cause energy waste[82]. And heat pump technology is a kind of equipment that uses electrical energy to convert low-grade heat energy into high-grade heat energy, which has a high energy conversion rate[85].

With the sustainable development and economic construction of eco-smart cities, clean energy methods such as electric heating and gas heating not only meet the needs of urban energy and society, but also improve the environmental protection level of eco-smart cities. Promoting electric energy replacement projects in cold areas in the form of electric heating has a broad application prospect. There are many forms of electric heating, improper ways can cause a lot of energy waste and environmental pollution, we must pay great attention and strict management. First of all, electric energy should not be regarded simply as a kind of clean energy. From the perspective of energy conservation and environmental protection, all kinds of direct electric heating should be strictly prohibited under normal circumstances. Secondly, it is recommended to promote the use of various heat pump technologies. Under the current policy environment in Jilin Province, a comprehensive platform for electric heating, energy storage and other interruptible loads can be considered, and electric heating loads below 10,000 kilowatts can be included in the market of electric auxiliary services in alpine regions to further reduce the operating costs of electric heating.

1.2 Status of Geothermal Energy Development

Energy consumption in buildings can be divided into heating, air conditioning, ventilation, hot water and lighting according to energy use, with HVAC and hot water accounting for more than two-thirds of the energy consumption[29, 86]. For the sustainable development of society, it is necessary to achieve a sustainable supply of energy without affecting economic development, and to solve the problem of environmental pollution in energy use projects[29, 87, 88].

Geothermal energy is low-grade thermal energy (usually low temperature) that occurs in surface water bodies such as rivers, lakes and oceans, as well as in rocky soil and underground water bodies below 200 meters[89, 90]. It is a new type of renewable energy formed by combining geothermal energy and solar energy[91]. Geothermal energy comes from two main sources: solar radiation and the decay of molten magma and radioactive materials deep in the earth. Soil, as an effective carrier of solar radiation, absorbs 46% of the solar energy, as shown in Fig 1-13. The total amount of geothermal resources worldwide is estimated to be about 1.45 × 1026 J, which is 17,000,000 times more than the total global coal reserves[92, 93]. The ASHRAE Design Manual [94]classifies geothermal energy into three categories: 1) high temperature geothermal energy above 150°C that can be used directly for power generation; 2) medium temperature geothermal energy below 150°C that can be used directly; and 3) ground source heat pumps (below 32°C). The first two categories can be classified as high-grade geothermal energy, while the third category is called low-grade geothermal energy. The use of high-grade geothermal energy such as hot springs for bathing has been known to our ancestors for thousands of years. Compared with the limited resources of high-grade geothermal energy, most of the world's geothermal energy has been stored in the form of low-grade energy in the soil, which mainly comes from the sun's radiation and can only be utilized in the form of ground source heat pumps at present[95].

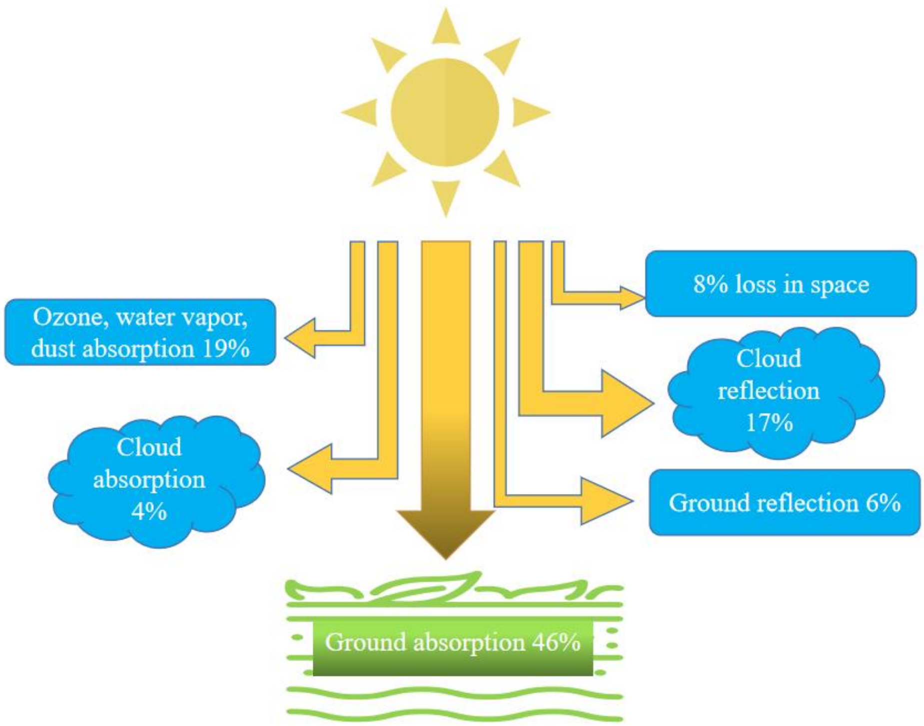

Fig 1-13 Solar Energy Distribution

Geothermal energy development and utilization is mainly through GSHP air conditioning system for heating and cooling of buildings, which is an economic and green way to use renewable energy[4, 96]. By using Geothermal Exchange pumps (GEP) or Groundwater heat pumps (GHP), the low-grade thermal energy (shallow geothermal energy) is extracted from the near-surface geotechnical body (including the underground water contained in it) to heat the building in winter; in summer, the heat is released into the near-surface geotechnical body to cool the building[97]. In summer, the buildings are cooled by releasing heat into the near-surface rock and soil. Since the heat-carrying mass in the ground source heat pump system is circulated in a closed circuit in the underground pipeline, it is relatively loosely restricted by hydrogeological conditions; therefore, it has become the shallow geothermal energy utilization pathway with the fastest development rate and the greatest application potential[98-100].

Research by the International Geothermal Association also indicates that the key growth markets for the geothermal industry will be the heating and cooling markets[101]. This shows that there is a large market demand in both international and domestic markets, providing a constant impetus for the future development of the geothermal energy market.

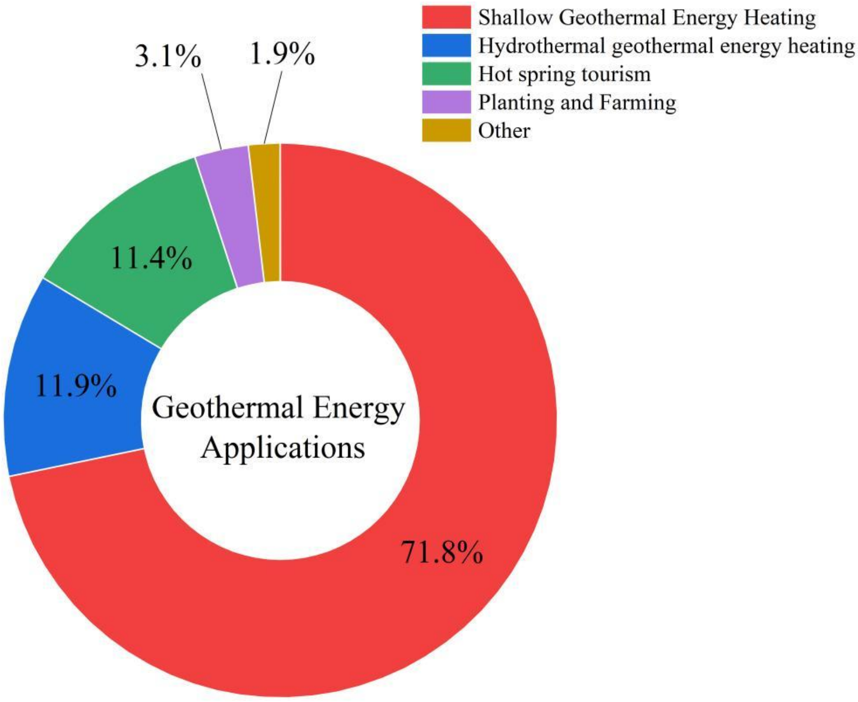

Fig 1-14 Global share of geothermal energy applications by 2020

From a worldwide perspective, countries such as the United States, Japan, Germany, Iceland, Australia are geothermal powers with good resource endowment conditions, leading technology and distinctive development models[102]. The lessons learned from the development of geothermal energy industry in these countries are of great value for the future development of geothermal energy industry in China[103, 104].

The U.S. is one of the most developed countries in the world in terms of geothermal power generation, and the oil crisis in the 1970s made successive U.S[105]. governments attach great importance to the issue of energy security. In this context, geothermal energy development and utilization has been supported by strong policies and has been developed steadily[100]. As early as the 1980s, the U.S. Department of Energy (DOE) and the Environmental Protection Agency (EPA) dedicated funds to promote the research and development and marketing of ground source heat pump technology[106]. 1998, the U.S. EPA issued regulations requiring the promotion and application of ground source heat pump systems in the buildings of federal government agencies nationwide[107]. As of December 2019, the installed base of ground source heat pumps in the

United States has reached a scale of more than one million units, generating more considerable economic and social benefits. A study supported by the U.S. Geothermal Association shows that geothermal use pays for itself in a five- to seven-year cycle, with annual savings of up to 70 percent in heating and cooling costs. This shows that the effect of the energy mix transition in the United States is very clear. This significantly reduces the incentive to develop new geothermal-based energy sources[108].

Japan is located in the combination of the Pacific plate and the extrusion zone of the Eurasian continental plate, its mountains, hills and lakes are usually the result of volcanic action, and there are more than 200 volcanoes distributed in Japan, 1/4 of which belong to active volcanoes[109]. According to the mechanism of geothermal resource formation, Japan's geothermal resource endowment is very rich. More importantly, Japan's geothermal resources are characterized by shallow heat source (usually less than 1,000 meters), abundant heat storage, high water temperature, high pressure, good replenishment conditions, and low cost of development and utilization. According to the statistics of the Japanese authorities, there are more than 2,800 geothermal (hot spring) sources in Japan, and there are as many as 27,000 geothermal wells[110]. In terms of the total amount of geothermal resources, Japan ranks 3rd in the world after Indonesia and the United States, with a power generation potential of more than 20 million kilowatts. According to the data released on the website of the Ministry of Economy, Trade and Industry of Japan, the total power of geothermal power generation in Japan is 500,000 kilowatts, which is about twice as much as wind power generation or three times as much as solar power generation, and the geothermal power stations are mainly concentrated in the Tohoku and Kyushu regions, accounting for 0.2% of the electricity market.

Germany is located on the European continent, and its geological structure and crustal activity are relatively stable[111]. Although there are tourist destinations like Baden-Baden, which is famous for its hot springs, the situation of geothermal resources in Germany is not optimistic. In 2007, some power plants in Germany started to generate electricity using generating units based on the Organic Rankinecycle (ORC)[112]. 2008 saw major breakthroughs in drilling technology and thermal storage technology in Germany. shallow geothermal energy development initially showed the characteristics of large-scale development. 2010, Germany in the city of Sauerrach, Redstad, Speyer and several other areas put in larger geothermal power generation facilities, the largest reached 10MW, geothermal power generation capacity of 7MW scale. 2013 November 11, Germany's first power station using geothermal power generation was officially put into operation. 2016, Germany Geothermal power generation capacity reached 42MW[113].

Iceland is located at the junction of the Asian-European plate and the American plate, and its geophysical characteristics are very obvious[114]. The complex topography, special geological structure and frequent crustal movements give Iceland's geothermal resources a unique advantage. According to the data released by the Icelandic National Energy Authority, there are more than 20 high-temperature geothermal areas, more than 250 low-temperature geothermal areas and more than 800 geothermal hot springs in Iceland. The geothermal resource content in the range of 10 km thickness of Iceland's crust is equivalent to 3×10^{16} degrees of electricity; the geothermal content in the range of 3 km thickness of the crust is 3×10^{15} degrees of electricity. If all of Iceland's geothermal energy is used to generate electricity, the annual power generation capacity can be more than 8×10^{10} degrees. As early as the 15th century, Icelanders began exploring the use of geothermal resources for production and living. In the early 20th century, the capital city of

Reykjavik began using geothermal resources for residential heating. After more than half a century of development, more than 98% of the residences in Reykjavik have access to geothermal heating services at low cost. The oil crisis that broke out in the early 1970s brought serious inflation and energy constraints to Iceland, which provided an important opportunity for the large-scale development and utilization of geothermal resources in Iceland. The opportunity. Driven by the energy crisis , the development and utilization of geothermal energy has received further attention from the Icelandic government. At the beginning of the 21st century, 85% of all Icelandic houses are centrally heated by geothermal resources, and the city of Reykjavik has achieved 100% geothermal heating and power supply, saving hundreds of millions of dollars in annual fuel expenses.

Geological factors are unique in that Australia has a world-class dry-heat rock resource. The country has a wide distribution of ultra-highly radioactive metamorphic granites; the country is gradually converging towards Indonesia in terms of continental plate movement, and active crustal movement has caused horizontal compression, generating sub-horizontal fractures and faults; sedimentary rock basins make up the vast majority of the country's land mass, providing not only a cap to block deep thermal fluid radiation, but also permeable aquifers.According to the survey of Australian scholars, the geothermal resources contained in the earth's crust above 150℃ within 5 km of the country could produce 3 million years of electricity for the entire population. In the 2004 White Paper "Securing Australia's Energy Future", the Australian Government listed Enhanced Geothermal Systems (EGS) as a technology with Australia as the market leader and committed support for geothermal exploration (research), evaluation (proof of concept), and demonstration projects. As of April 2008, the Australian Government has invested a cumulative $32 million in geothermal engineering and research[115].

Driven by the forces of Knowledge Society Innovation 2.0, Industry 4.0, Internet of Things, 5G technology, etc., new industries and new models have emerged in all walks of life, and geothermal energy industry is no exception. The "geothermal energy +" model formed around geothermal energy has already entered people's view. In essence, the "geothermal energy +" model has the characteristics of being driven by total factor productivity. In other words, the "geothermal energy +" model integrates various elements of geothermal energy development and utilization, and explores a new path of industrial development with the synergy of multiple elements[116].

Geothermal energy + at the planning level refers to the development of "deep geothermal energy + shallow geothermal energy + solar energy + industrial waste heat + sewage source heat pump + industrial waste heat", which is a "large geothermal" multi-energy complementary industrial development model. Through graded utilization and comprehensive planning, this model can play a role in protecting the energy consumption needs of urban and rural residents and helping to achieve green low-carbon development. Compared with other types of new energy such as solar energy and wind energy, one of the advantages of geothermal energy is that it can be used in a hierarchical way according to different temperatures. After the high temperature water is used for geothermal power generation, the residual water with medium temperature can also be used for geothermal heating, while the residual water after heating can also be treated and input into other pipelines for graded utilization. This makes full use of the temperature at each stage, which not only saves resources and improves efficiency, but also facilitates multi-angle benefits, and is an effective means to enhance the competitiveness of geothermal energy in general.

Geothermal Energy +" at the product level is based on the promotion of geothermal heating and the addition of cooling product modules. Currently, there are two main models of geothermal heating. One is small-scale geothermal wells for heating urban communities, and the other is scattered geothermal heat pump systems for heating. Large-scale centralized heating not only represents the development trend of geothermal energy heating, but also is an important reflection of clean energy consumption. Geothermal energy enterprises in some European countries can not only carry out geothermal heating, but also geothermal cooling. In the process of expanding the development mode of geothermal industry, this is also bound to be used by geothermal enterprises and research institutions in China. Under the "geothermal energy +" model, large-scale centralized heating will be combined with technologies such as ground source heat pumps for cooling, which can make more effective use of geothermal resources.

The 13th Five-Year Plan for the Development of Building Energy Efficiency and Green Buildings issued by the Chinese Ministry of Housing and Urban-Rural Development in March 2017 requires that by 2020[117], the energy efficiency level of new buildings in urban areas will increase by 20% compared to 2015, the proportion of green building area in new buildings in urban areas will exceed 50%, the proportion of renewable energy in urban areas will replace The proportion of conventional energy consumption in civil buildings exceeds 6%, and the new shallow geothermal energy building application area in cities and towns nationwide is more than 200 million square meters. The plan clearly states that, with regard to shallow geothermal energy building applications, the use of various types of heat pump systems will be promoted according to local conditions to meet building heating and cooling and domestic hot water needs. Improve the design and operation of shallow ground energy, fully consider the application resource conditions and the winter and summer balance of shallow ground energy applications, and reasonably match the units. Encourage the management and operation of energy stations in the form of energy hosting or contract energy management, etc., to improve operational efficiency. So far, all of China's provinces, municipalities directly under the Central Government, autonomous regions are shallow geothermal energy development and utilization project construction, the use of shallow geothermal energy heating and cooling units reached more than 5,000 of which about 80% are concentrated in northern China and the southern northeast.

Table 1-9 Geothermal heating area statistics for some provinces and cities during the 13th Five-Year Plan

Province and City	Hydrothermal type (10,000 square meters)	Shallow (10,000 square meters)	Total (10,000 square meters)
Hebei	15960	16080	32040
Shandong	6100	7000	13100
Henan	8910	3510	12420
Liaoning	-	6500	6500
Beijing	337	5683	6020
Tianjin	4000	1010	5010
Hubei	525	3400	3925
Shaanxi	830	2900	3730
Jiangsu	-	2697	2697
Anhui	10	1600	1610

Shanghai	-	1500	1500
Heilongjiang	600	-	600
Guizhou	-	500	500
Zhejiang	-	404	404
Shanxi	900	450	1350
Total	38172	53234	91406

In January 2017, the National Development and Reform Commission, the National Energy Administration and the Ministry of Land and Resources jointly issued the 13th Five-Year Plan for Geothermal Energy Development and Utilization, which requires the implementation of the 13th Five-Year Plan targets and tasks for geothermal resources in the region according to the actual situation. The introduction of these policies has created a favorable development environment for the development and utilization of geothermal resources.

Table 1-10 Future energy consumption forecast table

Year	Energy consumption (billion tons)	New Energy Consumption		Geothermal energy consumption		
		(billion tons)	Share of total energy consumption%	(billion tons)	Share of total energy consumption%	Share of new energy%
2020	45.0	6.75	15.0	0.50	1.1	7.4
2030	55.0	13.75	25.0	1.00	1.8	7.3
2050	65.0	26.0	40.0	2.00	3.1	7.7

(Source: "Bringing into play the advantages of geological exploration team and promoting geothermal resources development", Bin Dezhi, 2015.6)

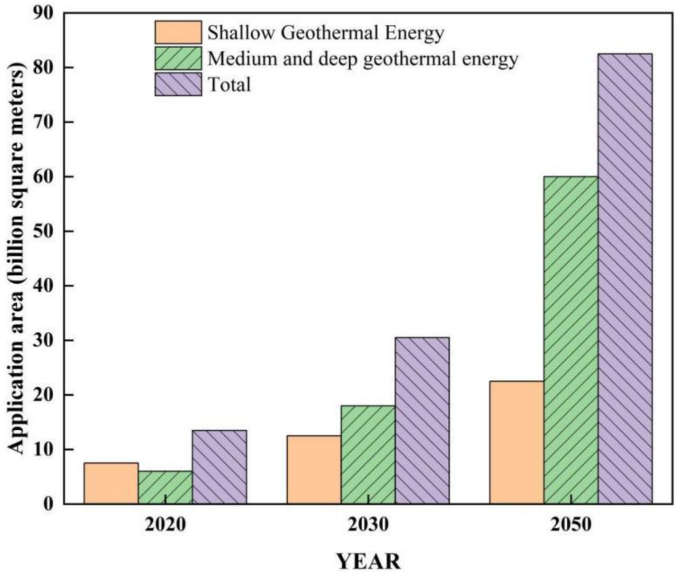

Fig 1-15 The overall goal of the future development of geothermal heating and cooling
(Source: "Bringing into play the advantages of geological exploration team and promoting geothermal resources development", Bin Dezhi, 2015.6)

The existing building area in China is over 50 billion square meters, and the completed housing area in the country is about 27.8 billion square meters in the 10 years from 2004 to 2013, and the new building size is about 2 billion square meters per year. Based on 50% of the buildings needing heating, the existing building heating area in China is over 25 billion square meters, and the new building heating area is over 5 billion square meters. If 5% of the existing building area and 40% of the new building area is heated by ground source heat pump, the heating area can reach 3.25 billion square meters, with a potential market size of 1 trillion yuan. Compared with the direct use of electric boilers for heating (saving 70% of the total distribution capacity), it saves 316.875 billion kWh of electricity, 110.963 million tons of standard coal, 277.2658 million tons of carbon dioxide, 4.817 million tons of particulate matter, 2.6396 million tons of sulfur dioxide and 1.9194 million tons of nitrogen oxides per year. It is equivalent to reduce the construction of a 188.5GW power plant, saving about 747.5 billion yuan of investment in thermal power plants.

In the context of clean and environmentally friendly energy becoming more and more mainstream energy utilization, shallow geothermal resources are introduced to China as an emerging way of geothermal resource utilization and gradually promoted and developed.

1.3 Status of ground source heat pump development

1.3.1 Status of GSHP development and application in the world

In 1912, H. Zoelly (Switzerland), proposed the use of geotechnical bodies as heat pump heat sources, thus starting the research of ground source heat pumps[118]. The middle of the last century, ground source heat pump systems were introduced in the U.S. building sector, using groundwater and river and lake water as the heat source medium to meet people's heating needs.

However, in this process, because ground source heat pump systems are direct systems, the soil is susceptible to corrosion and other effects, resulting in the use of heat pump systems for a very limited period of time, so the reliability of ground source heat pump systems has been questioned by various sectors of society. As time went on, interest in groundwater heat pumps was renewed in the late 1970s and early 1980s due to the shortage of energy.

In 1998, the United States began to promote the application of soil source heat pump systems[119], and the President of the United States, in order to show his support for new energy technologies, directly installed ground source heat pump systems in his own residence. In the 21st century, the U.S. construction industry has shown a ferocious development trend, so the ground source heat pump has also been fully developed. At that time, the development of ground source heat pump has always maintained a rate of over 15%.

Until 2005~2007, ground source heat pumps in the United States reached the peak of development, widely used in various states, the total number of ground source heat pumps has more than 45,000 units[120]. At the same time, in order to promote the further development of ground source heat pump systems, the U.S. government launched a series of incentives, as shown in Table 1-11. The research on ground source heat pump technology in Europe started in the middle of last century, but at that time, the heat source ground pump technology was not widely used[121]. This is mainly because the energy price was generally low at that time, while the price of ground source heat pumps was high. With the first oil crisis, many countries began to recognize the problem of gradual energy shortage, for example, the U.S. and Japanese governments are actively promoting the advantages of ground source heat pump technology, which can reduce the country's energy consumption. But at this time, European countries still do not have a lot of interest in ground source heat pump technology, mainly because at this stage, solar technology is more favored by the EU governments.

However, with the outbreak of the second oil crisis, European countries began to realize the advantages of ground source heat pump technology, so they began to promote ground source heat pump technology among the population. During this period, European people's heating and domestic water heat source are from the heat pump system. With the continuous consumption of energy, the price of energy has been increasing in recent years, in addition to the process of energy consumption can also cause great damage to the environment, so many countries have begun to enact laws to limit energy consumption. In the case of restricting energy consumption, European countries have started to promote ground source heat pump technology in order to ensure that the normal life of the residents is not affected, so they continue to innovate it so that it can The ground source heat pump technology is a good alternative to traditional energy sources. In this context, ground source heat pump technology has once again ushered in its own golden period of development. Since the late 1980s, with the deepening of the understanding of technology and the gradual attention of society to environmental issues, ground source heat pump technology has gained rapid development and the scale of application has expanded rapidly[122]. At present, ground source heat pump air conditioning systems, accounting for more than 50% of the total air conditioning of buildings in countries such as Austria, Germany, Sweden and Finland, and more than 20% in the United States[123].

Table 1-11 Future energy consumption forecast table

State	Projects	Content of measures
Illinois	The Gowernor’s Small Business Smart Energy Program(SBSE)	Through the assessment of existing buildings, we will provide them with corresponding energy-saving improvement plans. At the same time, the government will provide a comprehensive fundraising mechanism.
Indiana	Indiana Energy Education＆Demonstration Grant Program	Incentives for commercial and local government sector projects that use renewable energy and implement energy efficiency measures.
Massachusetts	Sales Tax Exempyion	Individual residences within the state that use ground source heat pump systems are exempt from from the 5% state sales tax, but does not cover commercial construction. Commercial buildings are not covered.
	Green Schools Initive	Information support and political participation in the design and construction of feasibility studies for renewable energy projects. The grant includes $20,000 for the feasibility study process and $639,000 for the design and construction

		process. At the same time, schools that use renewable energy will receive free The project will also provide free green awareness and education activities for schools that use renewable energy.
	Residential Tax Credit	For residents who install a ground source heat pump system, they can apply directly for apply for a $1,500 tax credit.
Montana	Universal System Benefits Program Renewable Energy Fund	North Western Energy provides cyclical financial support for project work that uses renewable energy.
New York State	New York Energy Smart Loan Fund	For projects that use energy efficiency measures and renewable energy, the interest rate on the loan is reduced to a certain extent.
	New construction Program	exceed the requirements of the national energy-saving standards, a direct award of 50,000 USD.
	Flex Tech Service for Energy Feasibility Studies	Incentives for individual and commercial households that adopt ground source heat pumps 150-250 USD/household.

In the 1950s, Ingersoll and Plass et al[124]. constructed the basic theoretical model of heat transfer in ground source heat pump systems and gave the corresponding analytical solutions to provide the corresponding calculations for system design, which provided the theoretical basis for the technical and application research of ground source heat pump systems. As shown in Table 1-12 starting from the 1970s, mainly based on the above basic theory, the experimental and In this stage of research process, the focus of research and application gradually focused on ground source heat pump technology in the form of vertical buried pipes. At present, the ground source heat pump technology in the form of vertical buried pipes has been widely used in residential and commercial buildings, and it is estimated that the application area of ground source heat pump systems in the form of vertical buried pipes is increasing rapidly at a rate of 10%-30% worldwide each year.

Table 1-12 Related research and results[125]

YEAR	Author	Research Content	Main results
1948	Ingersoll	Buried pipe heat transfer technology	Buried tube heat exchanger line source theory
1965	Carslaw	After considering the flowing liquid energy, the theory of columnar heat source is proposed	Constant heat flow model
1972	Jaeger	After considering the flowing liquid energy, the theory of columnar heat source is proposed	Constant wall temperature model
1983	V.C.Mei	Based on energy balance, this heat exchange model is proposed	Three-dimensional transient far boundary

			heat transfer Model
1985	Hellstrom	A semi-empirical model and its analytical solution are given for the problem of thermal resistance of multiple heat transfer tubes in a borehole under two-dimensional conditions, based on a column heat source	Hellstrom column heat source model
1987	Eskilson	Improvements to the line heat source theory and column heat source theory considering the basis of heat flow variation at different depths within the buried tube heat exchanger	Eskilson Model
1996	Muraya	The thermal thermal short circuit between two branches of a U-shaped buried tube heat exchanger was studied Problem	Muraya Model

A CFD model (three-dimensional computational fluid dynamics model) on the ground source heat pump system was developed through the continuous efforts of Yuanlong Cui[126] and others, which investigated the heating performance of the system under continuous and intermittent operating conditions and evaluated the system thermal energy output and performance coefficients. The k-ε equation describing the turbulence phenomenon in the u-tube was solved using computational fluid dynamics (CFD) software. The experimental results show that the soil temperature under intermittent operation is higher than that under continuous operation.

The intermittent operation not only helps to recover the soil temperature, but also improves the performance of the system, which is very beneficial to the long-term operation of the system.

1.3.2 Status of GSHP development and application in China

Since the reform and opening up in 1978, while the level of urbanization in China is rapidly improving, urban building renovation and new construction, showing a continuous acceleration of development[57]; at present, China's annual completion of housing construction area of about 1.6 billion to 2 billion m^2, is expected to the end of 2020, China's new construction area of nearly 20 billion m2. due to China's geographical location and climate characteristics, the vast majority of buildings need At the same time, with the improvement of people's living standard, the whole society attaches importance to environmental protection and energy conservation and emission reduction, the application of ground source heat pump technology in China has gradually shown a trend of accelerated development under the strong support of national policies, which also brings great development potential for the application of ground source heat pump technology. The development of ground source heat pump systems in China has entered a rapid development stage after the initial stage from the 1980s to the beginning of the 21st century and the initial promotion stage from the beginning of the 21st century to 2004[127].

Compared with other countries, China still has a pioneering position in this field of ground source heat pump system. Since the 1990s, research on related technologies has been started, but the research progress and achievements were limited due to the lack of advanced research conditions at that time. With the deepening of research and the progress of science and technology, the research progress in ground source heat pump system in China has accelerated and the restrictions have become less and less, and at the same time, after the research cooperation between China and the United States in related fields, the research in this field in China has also made a qualitative breakthrough, and the ground source heat pump related technology can be applied in the real sense in China's engineering, and the development of ground source heat pump technology in China is divided into three stages[128]:

The first is the start-up phase, which in time is from the end of the last century to the beginning of this century. At the end of the last century, China began to carry out research on heat pump technology, in time this is earlier than other countries, from 1978 onwards, the Chinese refrigeration society and the Chinese building society respectively carried out refrigeration and heat pump related aspects of the discussion, after this, China scientific researchers gradually have more knowledge of ground source heat pump technology, in 2002 China for heat pump technology and held a World-wide technical seminar.

In the initial exploration of ground source heat pump technology, equipment manufacturers and integrators used the Post and Telecommunications New Village project in Liaoyang City to test the water for this technology. In China, the ground source heat pump system was gradually understood and accepted by practitioners from all walks of life and began to take the initiative to learn this highly efficient and energy-saving system only after China and the U.S. cooperated strategically on the ground source heat pump system at the national level and gave special guidance and support to the system, while the cooperation had a profound impact on the initial development of China in this field. Although at this stage, many professionals or professional industry enterprises know more about ground source heat pump, and they are also optimistic about the development prospect of ground source heat pump, but due to the influence of the immaturity of ground source heat pump technology at this stage, the incompleteness of the relevant software and hardware supporting, the market recognition of the system is not high and other defects, the development of ground source heat pump in China at this stage is not optimistic, therefore, this stage is the ground source heat pump in China Therefore, this stage is the initial stage of ground source heat pump in China.

The second is the promotion stage, the stage in time is 2000 to 2004. At the beginning of this century, ground source heat pump in our The ground source heat pump system was widely used in cities at all levels in China, and at the same time, manufacturers of water source heat pump The manufacturers of water source heat pump units are also mushrooming and developing rapidly, and by the end of 2004, there were nearly 100 of these manufacturers in China. More At this stage, both the number of patents on ground source heat pump systems and the number of papers published by relevant universities are very large, which is sufficient to show that the research on ground source heat pump systems from all walks of life in China at this stage can be described as "a hundred schools of thought". In this century, the literature on ground source heat pump system translated by our scientists provides a lot of reference basis for our scientists in this field of ground source heat pump system. Since the ground source heat pump has been greatly developed at this stage, it has also revealed many problems regarding the ground source heat pump. For example, the lack of training for technicians in this field has limited the technical level of technicians, thus making the general public have doubts about it. At the same time, because the real estate development enterprises attach more importance to the interests than to the new technology, the ground source heat pump manufacturers have difficulties in marketing their products, and the development of enterprises is also limited.

The third phase is from 2005 to the present, which is the rapid development phase. During this period, China has fully recognized the importance of environmental protection and energy conservation.

The importance of environmental protection and energy conservation has been fully recognized, so many laws and regulations on environmental protection and energy conservation have been enacted during this period, which makes China's energy and environment fully protected. In order to guarantee the energy needed for the high speed of China's economy, China began to actively look for new ways to use energy, in this process, ground source heat pump technology is highly concerned by the relevant departments in China because of its energy-saving advantages. Under the vigorous promotion of government departments, a large number of manufacturers of ground source heat pump systems have emerged in China. Through the strong support of the government, these enterprises have enough funds for technological innovation, so the ground source heat pump technology in China has developed rapidly during this period.

After rapid development, China's ground source heat pump system has now formed a completed industry chain, with the entire industry chain of the total number of enterprises is more than 400. According to the data released by the relevant departments, there are more than 7,000 ground source heat pump systems under construction in China, with a total construction area of 139 million square meters. The distribution of the project is, north and northeast China Compared with the land, the southern region pays less attention to ground source heat pump systems. At present, the heat sources of ground source heat pump systems in China are mainly divided into the following four types: soil source, groundwater source, surface soil source, groundwater source, surface water source, and sewage source. The proportion is 32%, 42%, 14% and 12% respectively.

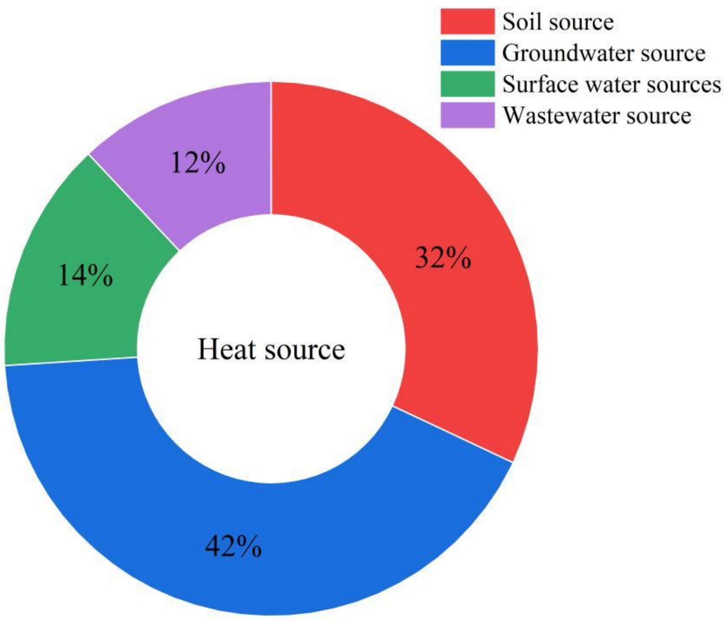

Fig 1-16 Classification of heat sources

According to the 2022 China heat pump industry research report data show that, with China's 2030 carbon peak target and the related policies of the successive. The market size of China's heat pump industry will rise sharply in 2021 compared with 2020, reaching 24.8 billion yuan, a year-on-year growth of about 23%, and is expected to continue this upward momentum in 2022, with the industry market size expected to exceed 30 billion CNY[129].

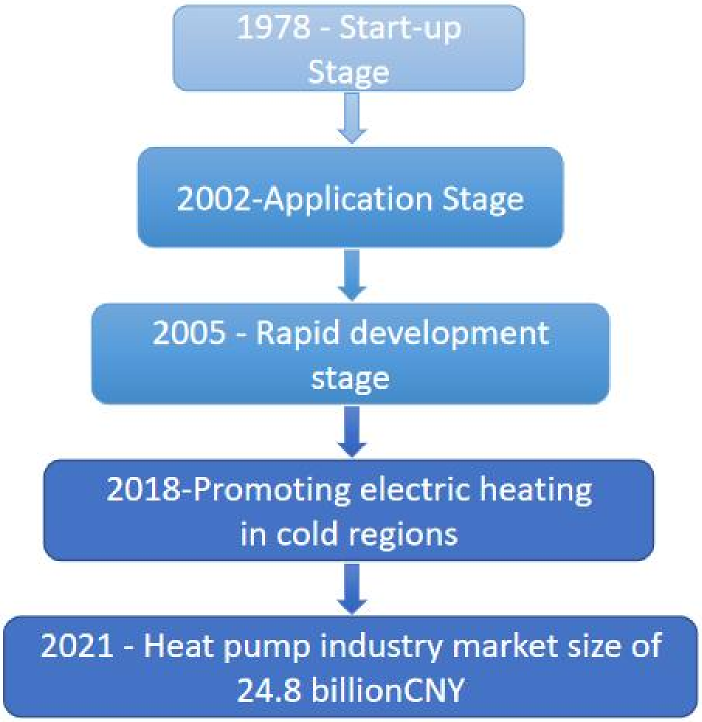

Fig 1-17 History of ground source heat pump

Ground source heat pump technology started early in China and was able to develop rapidly thanks to the national promotion policy on the one hand, on the other hand, because of the unremitting efforts and contributions of many researchers, university teachers and students, research scholars, etc., and the application of their research results in practical engineering, contributing to green, energy saving and emission reduction. However, it is worthwhile to study in depth how to keep the system stable and efficient in the application process, as well as the economic and environmental benefits brought by the application.

1.4 Research purpose and logical framework

1.4.1 Research purpose and core content

Ground-source heat pumps (GSHPs), as a resource-rich, clean, environmentally friendly, efficient and stable new energy source, are a rapidly developing alternative energy source, especially suitable for winter heating in cold regions of northern China, but because the heat load in winter is much greater than the cold load in summer in cold regions, the ground-source heat pump system will produce thermal imbalance in the underground temperature field after long-term operation, which will affect the operational performance and service life. Therefore, in this paper, a ground source heat pump in a public building located in the cold region of Changchun, China, which has been in operation for 8 years, is selected as the subject of study. Through a combination of simulation and monitoring data analysis, a comprehensive evaluation of the economic environment and energy saving of the system is made based on the analysis of the thermal balance of the underground temperature field and the operational performance of the system, which provides a basis for the application and promotion of ground source heat pump systems in cold regions, and provides a basis for the design and construction improvement of ground source heat pumps. It also provides support for the improvement and optimization of ground source heat pump design and construction.

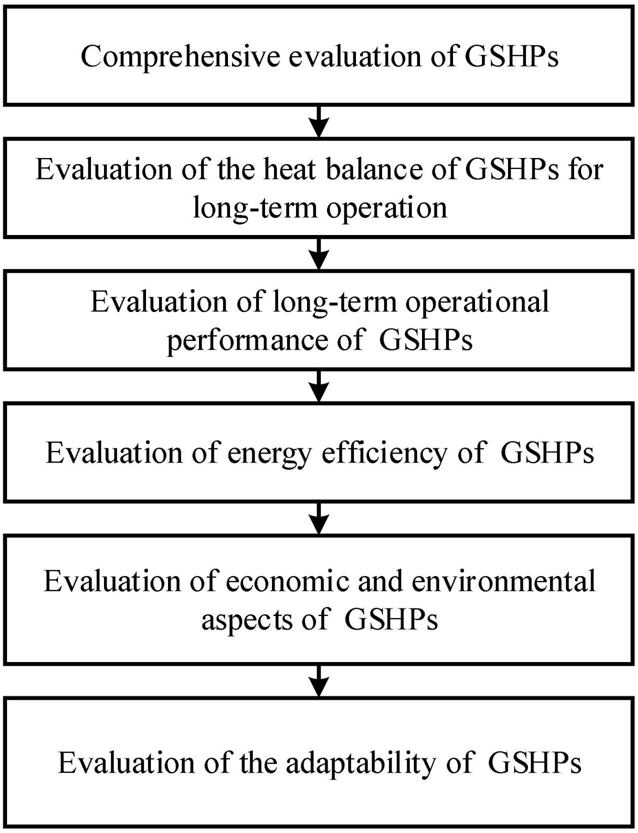

Fig 1-18 Research logic of the study

1.4.2 Chapter content overview and related instructions

The chapter names and basic structure of this study are shown in Fig 1-19 and the brief chapters are shown in Fig 1-20

Research background & Purpose	**Chapter One** Research background and purpose	
Literature review	**Chapter Two** Literature review on ground source heat pump systems (GSHPs)	
Research Subjects & Methods	**Chapter Three** Research subjects and methods	
Soil heat balance	**Chapter Four** Study of soil heat balance of GSHPs	
Benefit Analysis	**Chapter Five** Energy efficiency analysis of GSHPs	**Chapter Six** Economic and environmental analysis of GSHPs
Conclusions	**Chapter Seven** Conclusion and prospect	

Fig 1-19 Chapter names and basic structure

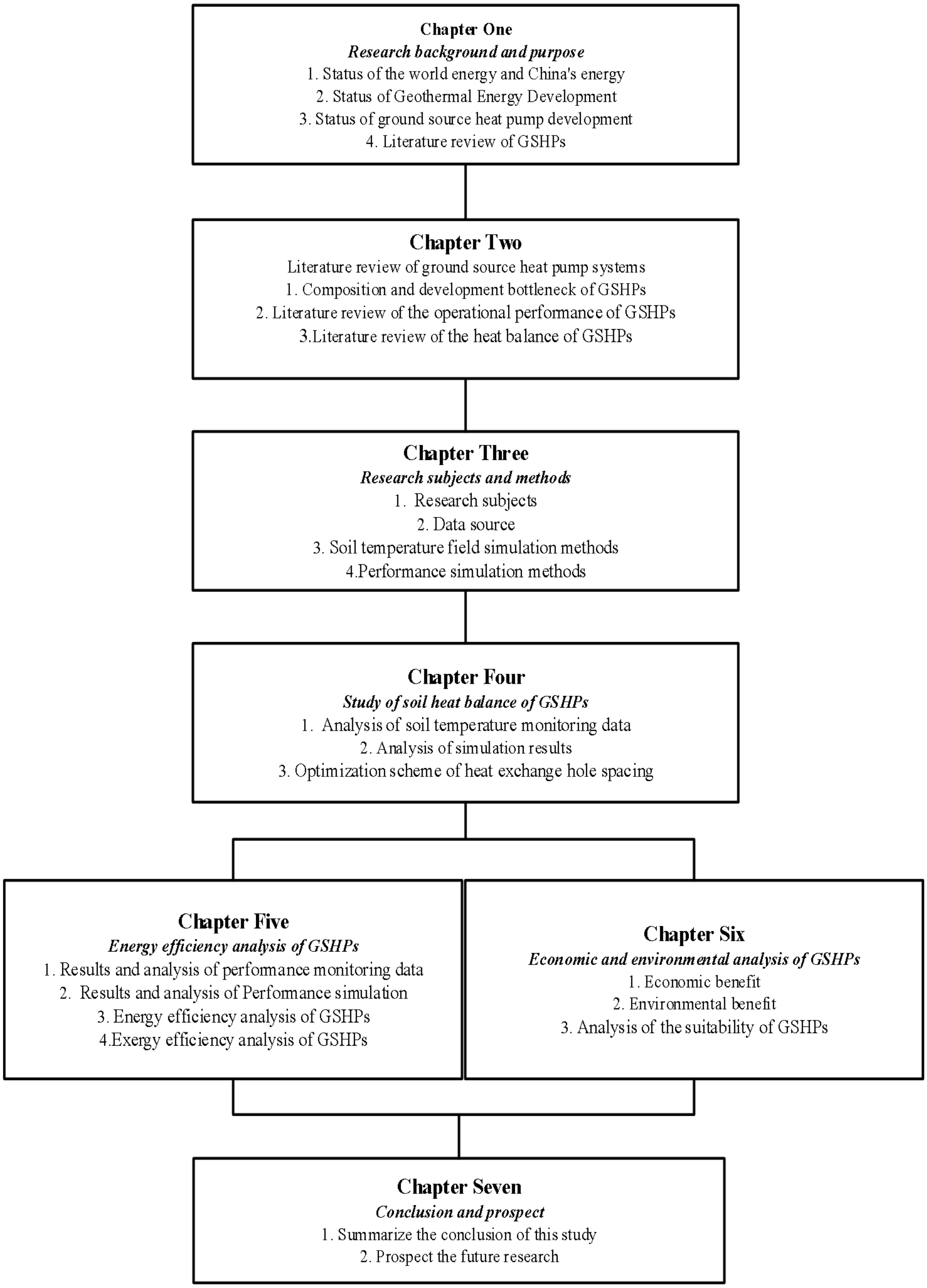

Fig 1-20 Brief chapter introduction

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Chapter 2

LITERATURE REVIEW ON GROUND SOURCE HEAT PUMP SYSTEMS

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2.1 Classification of heat pump

Heat pump is an energy-saving device that converts natural low-level heat energy (air, water, soil, solar energy, industrial waste heat) into high-level heat energy by consuming high-level energy (electricity, coal, oil, natural gas) through upgrading[1]. From the perspective of energy conservation, heat pumps not only follow the first law of thermodynamics. It also follows the second law of thermodynamics. By consuming a certain amount of high energy cost, the heat is transferred from the low temperature heat source to the high temperature heat source. The heat obtained by the heat pump is the sum of the consumption of high level energy and the absorption of low temperature heat source energy[2]. The performance index of a heat pump is generally measured by the Coefficient Of Performance (COP) of the heat pump. Energy efficiency ratio is defined as the ratio of cooling capacity (or heat production) to shaft power (or input power). Generally, the COP of domestic heat pumps in China is about 3-4, that is, the heat pump can extract 3kW to 4kW of heat energy from low temperature heat sources (water, air, soil, industrial waste heat, etc.) for every 1kW of electrical energy consumed. Therefore, heat pump is a representative energy-saving device[3].

The heat pump system consists of a heat pump unit, a high level energy transmission and distribution system, a low level heat energy collection system and a heat distribution system[4]. The heat pump system can change the heat energy not directly available in the heat source into renewable heat energy that can be directly used by heat users[2].

The components of a heat pump unit are compressor, condenser, evaporator, throttling mechanism and auxiliary equipment, etc. The absorption heat pump uses a combination of generator and absorber to realize the compressor function. The basic principle of heat pump is Carnot cycle, the high temperature and high pressure steam discharged from the compressor enters the condenser, the refrigerant vapor is condensed into liquid refrigerant (liquefied) after exothermic to the high temperature heat source[5, 6], the liquid mass is expanded by the throttling device and then enters the evaporator, the gas-liquid mixed refrigerant absorbs the heat from the low temperature heat source (air, water or soil, etc.) in the evaporator and evaporates to form vapor (vaporization), the refrigerant vapor is sucked in again by the compressor to complete a cycle[7]. The refrigerant vapor is sucked in again by the compressor to complete a cycle and prepare heat energy again and again[8]. The heat from external low temperature air, water or soil is pumped to the user at higher temperature, so it is called heat pump.

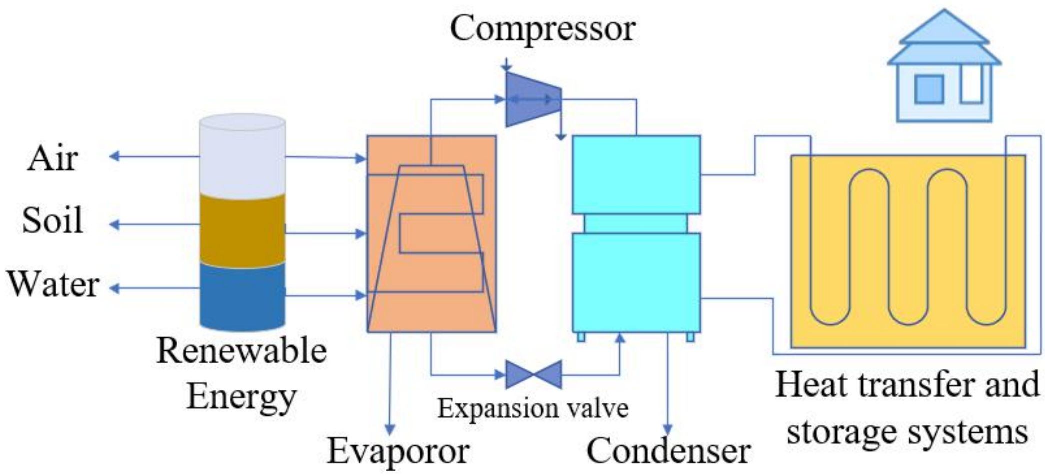


Fig 2-1 Heat pump technology principle

According to the different types of low-level heat sources, heat pumps can be divided into air source heat pumps[4], water source heat pumps, ground source heat pumps, etc., which collect heat from outdoor air, water or ground, respectively, and concentrate it for indoor use. Taking indoor heating as an example to illustrate the energy-saving effect of heat pumps, if supplying 10kw of heat to maintain the room temperature of 20℃ indoors, using coal-fired heating needs to supply 14.286kw of chemical energy (coal-fired efficiency is taken as 70%) and emit a large amount of pollutants; using resistance heaters, directly heating the indoor air, at least 10kw of electrical energy needs to be supplied; while using electrical energy to drive the heat pump to heat the room, only 2.857kw of electrical energy is consumed (COP takes 3.5), heat pump heating reduces a large amount of high energy consumption[9].

2.1.1 Air source heat pump

The source of heat and cold in an air source heat pump is the outdoor air. The principle of air source heat pump is to absorb heat in the outdoor air, heat the refrigerant (fluorine) in the evaporator to vaporize it, compress the refrigerant vapor through the compressor, enter the condenser, release the heat to the water in the tank and condense and liquefy it, then return to the outdoor unit after cooling and depressurizing by the throttling device[10]. There are two types of air-source heat pumps: air-to-air heat pumps and air-to-water heat pumps[11]. With air-to-air heat pumps, the medium of heat exchange with both indoor and outdoor heat exchangers is air. A four-way reversing valve is used to switch between winter and summer functions[12]. Air-water heat pump has a heat exchanger which is refrigerant-water heat exchanger[13]. In winter heating, refrigerant-water is used as condenser, and in summer cold, refrigerant-water is used as evaporator. Air-source heat pumps have environmental adaptability problems. The normal operating temperature of most air-source heat pumps is between 0-40℃. Since the ambient temperature is higher in the south, air-source heat pumps perform better[14]. The winter temperature in northern cities is only -10℃:, so there is a defrost problem in northern areas. Cold areas are not suitable for the use of air source heat pumps, because the temperature is too low air source heat pump units can not start[15].

Table 2-1 Air source heat pump features[16]

Features	Description
Low level heat source	Low-level heat sources are most prevalent. Air exists everywhere in space, is available at all times, and is available in quantity as needed. This makes the installation and use of air source heat pump units relatively simple and convenient, and the application is also the most common[17]. The application is also the most common.
Outdoor side heat exchanger	The outdoor side heat exchanger is easy to frost in winter. When the air source heat pump unit operates in winter, when the outdoor air side heat exchanger surface temperature is lower than the dew point temperature of the surrounding air and lower than 0℃[18]the heat exchanger surface will be frosted. Unit Frost will reduce the heat transfer coefficient of the heat exchanger on the outdoor side and increase the flow resistance on the air side, resulting in a decrease in the unit's COP and heating capacity of the unit will be reduced[4]. Therefore, air source heat pump units generally have the necessary defrosting system or anti Frost prevention measures.
Unit operation	The operation of the unit has some noise. Air source heat pump units generally do not need enclosure structure and are arranged outdoors; the heat capacity of air is smaller than that of water[19]. The heat capacity of air is smaller than that of water, and under the same heat exchange requirement, the air source heat pump unit requires a much larger amount of air than water. The heat capacity of air is smaller than that of water[20].

2.1.2 Water source heat pump

Shallow water sources on the Earth's surface (generally within 1,000 meters), such as groundwater, surface rivers, lakes, and oceans, absorb a considerable amount of the Sun's radiating energy into the Earth, and their temperatures are generally stable[21, 22]. The working principle of water source heat pump technology is to realize the transfer of heat energy from low temperature to high temperature by inputting a small amount of high grade energy (such as electric energy)[23]. Water is used as the heat source of heat pump heating in winter and the cold source of air conditioning in summer[24]. That is, the heat in the building is taken out in the summer and released into the water body. Because of the low temperature of the water source, the heat can be efficiently taken away to achieve the purpose of indoor refrigeration in the building in summer[25]. And winter is through the water source heat pump unit, extract heat energy from the water source, to the building heating[26].

Compared with boiler (electricity, fuel) and air source heat pump heating system, water source heat pump has obvious advantages. Boiler heating can only 90%-98% of the electric energy or 70%-90% of the fuel internal energy into heat[27], for the user to use, so the ground source heat pump than the electric boiler heating to save more than two-thirds of the electric energy, than the fuel boiler to save more than half of the energy; Because the heat source temperature of the water source heat pump is stable throughout the year, generally 10-25℃, its refrigeration and heating coefficient can reach 3.5-4.4, compared with the traditional air source heat pump, it is about 40% higher, and its operating cost is 50%-60% of the ordinary central air conditioning[28].

Table 2-2 water source heat pump features[29]

Features	Description
Relatively stable water body temperature	The temperature of the water body is relatively stable and its fluctuation range is less than that of air, and the available water body temperature can be used in summer and winter to provide relatively low condensing temperature and high evaporating temperature[30]. Therefore, the water source heat pump unit The operation of the water source heat pump is stable and reliable, and there are no problems such as winter defrost of air source heat pump.
Suitable for medium to large scale projects	The complex water intake structure is more suitable for medium - scale engineering. Large water source heat pump unit heating capacity The force is usually about 1000-3000kw, which is used for the heat supply of water source heat pump units in large heat pump stations[31] The force can reach 15MW, 20MW, 25MW, 30MW.
Application of water source heat pump	Suitable for areas with abundant water resources. First of all, we need to understand the local water source situation, conduct a thorough investigation of the water source situation and determine the water use plan.
Refill method	If groundwater is used, the recharge problem must be considered, and the recharge method should be considered according to the local geological conditions. Recharge difficulty is the problem encountered by most projects at present, the application of groundwater ground source heat pump needs to be careful[17].

2.1.3 Ground source heat pump

Ground source heat pump system relies on the underground water body and geotechnical body, which are endowed with shallow geothermal energy, as the heat energy endowment, and generally water is used as the carrier of heat transfer to transfer the heat from the heat energy endowment to the building in winter and the heat generated by the system for cooling the building in summer to the heat energy endowment[32].

In the early stage of ground source heat pump technology and theory, the focus was on heating in cold areas, so the underground geotechnical body and underground water body, which are endowed with a certain amount of heat, were used as the heat source for heating, and the corresponding application and theoretical research was carried out; with the research and application of ground source heat pump technology[33], the underground geotechnical body and underground water body can not only provide a certain heat source for the system in winter, but also allow the system to transfer the heat generated during cooling in summer. In other words, the underground geotechnical body and the underground water body are essentially thermal energy saving bodies with certain heat regulation capability; the heat regulation capability of the saving bodies is especially valued in the areas of combined cooling and heating, which also derives the concept of heat balance of the underground heat exchange system[9, 34].

Depending on the thermal energy donor, ground source heat pump systems can be divided into Surface-Water Heat Pump (SWHP), Ground-Water Heat Pump (GWHP) systems, and Ground-Coupled Heat exchanger (GCHP) systems[35], which are also commonly referred to as ground source heat pumps or ground-coupled heat pumps (GCHP)[36].

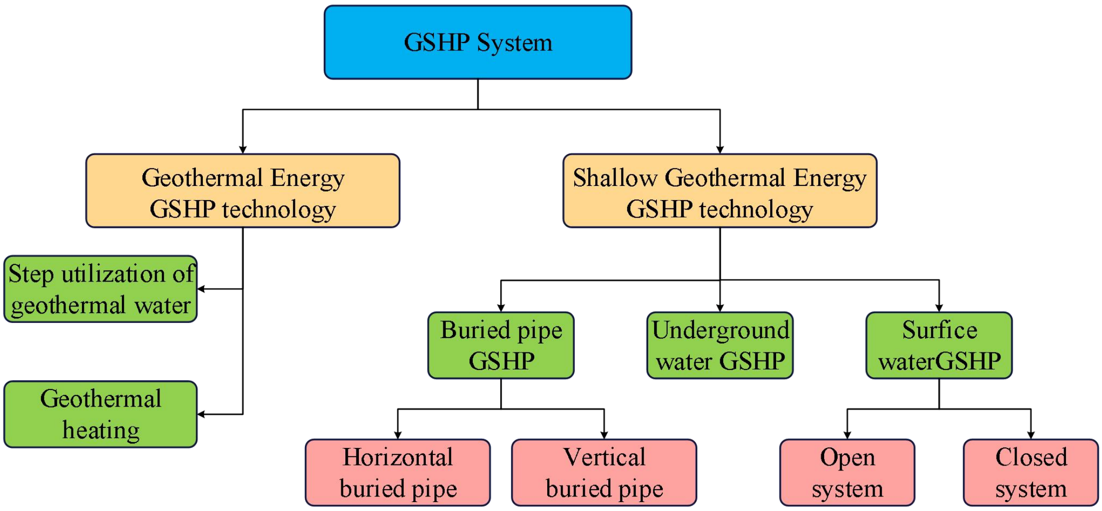


Fig 2-2 Classification of ground source heat pump systems

(1) Underground water source heat pump

A heat pump system that relies on a water source endowed with shallow geothermal energy (or other forms of thermal energy) and uses water as a vehicle for heat transfer, where the heat from the water source is transferred to the building in winter and the heat generated by the system is transferred to the water source in summer when the building is cooled[35, 37].

Water source type heat pumps include surface water source heat pumps and ground water source heat pumps[38]. Surface water source heat pumps are water source heat pumps that use surface water bodies of rivers, lakes and reservoirs as heat energy reservoirs[39]. According to whether the system takes water from the water source or not, there are two types of open system and closed system. Surface water source heat pumps, which are limited by the distribution conditions of surface water bodies, are often also constrained by the fact that the temperature variation range of the water body is often opposite to the demand (high water temperature in summer and low water temperature in winter), making the application restricted; in addition, open systems have a certain degree of influence on the water quality of the target water source[40].

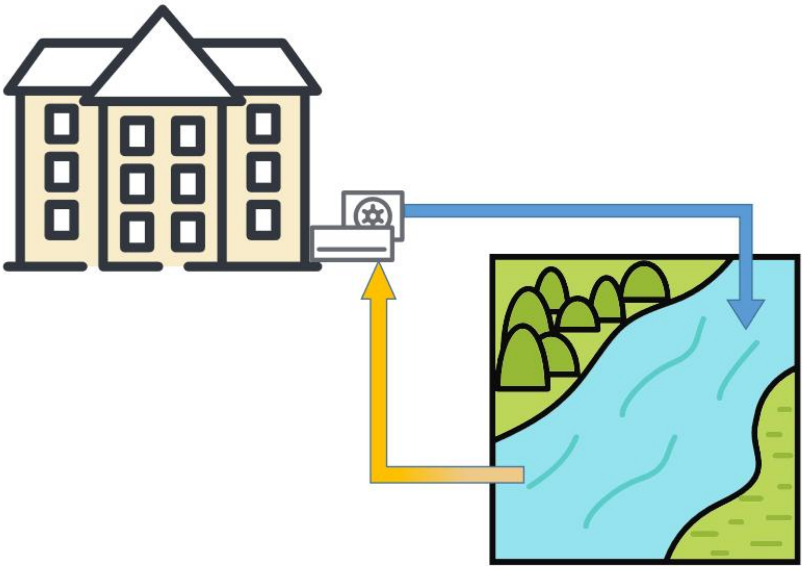
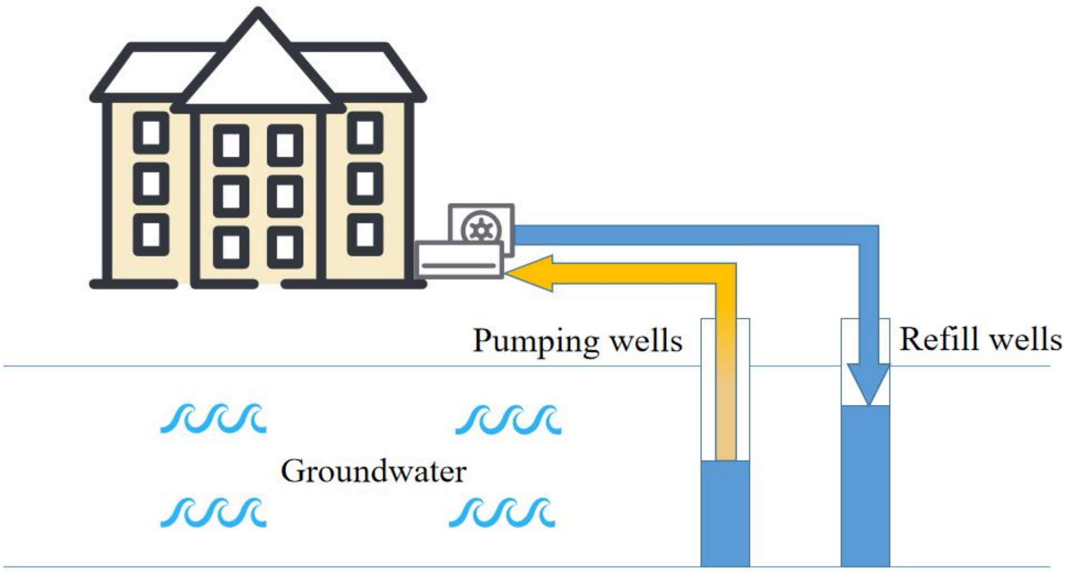
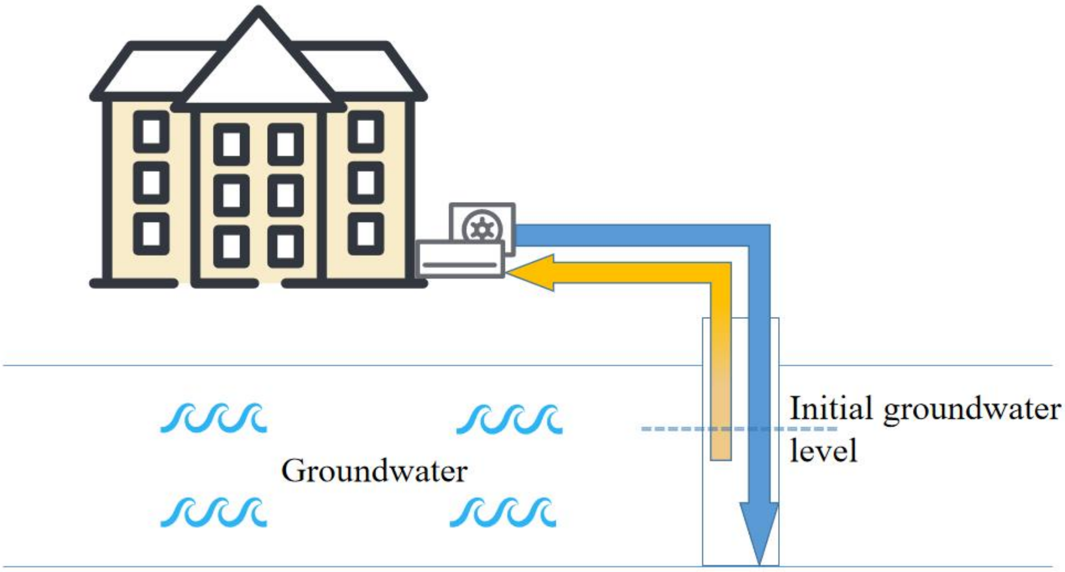


Fig 2-1 Diagrammatic sketch of water cycle about surface-water source heat pump

Groundwater source heat pumps are water source heat pumps that use groundwater in aquifers as a thermal energy donor[41]. According to the combination of water extraction (pumping) wells and recharge wells, they are divided into two types: different well recharge and same well recharge [42]. Groundwater heat pump systems, not only are limited by groundwater extraction and recharge conditions, but also have a degree of uncertainty about the geological environment of the water source[43].



A. Different well pumping system



B. Same well pumping system

Fig 2-2 Diagrammatic sketch of water cycle about ground-water source heat pump

Table 2-3 Water source type heat pump working principle

System Type		Working Principle
Surface water heat pumps	Open system	Water is taken from the target water body, passed through the air conditioning compressor, and then returned to the target water body[44]
	Closed system	The heat exchanger tube is buried in the surface water body, and the water as the heat carrier exchanges heat with the surface water body outside the tube through the tube wall during the closed circuit circulation in the heat exchanger tube[45].
Groundwater heat pumps	Different well pumping system	Projects that use different wells for water extraction and recharge, the extraction and recharge wells are mostly operated on a rotational basis.
	Same well pumping system	Water withdrawal and recharge occur in the same well

(2) Ground source heat pump

Ground source heat pump buries the heat exchanger tube at a certain depth below the ground surface, and the water, which is the heat carrier, circulates in a closed circuit inside the heat exchanger tube and exchanges heat with the rock and soil outside the tube, where shallow geothermal energy is stored, through the wall of the tube[46]. The geotechnical body is better able to ensure the stability of the heat sink because it generally does not vary much in temperature while generating a lot of heat. Ground source heat pump system includes outdoor ground energy heat exchange system, heat pump unit and indoor heating and air conditioning system[25].

In the cooling condition, the cycle of vapor-liquid conversion is realized, which requires the compressor inside the ground source heat pump unit to do work on the refrigerant in the cooling condition[47]. That is, the heat generated during the circulation of air inside the house needs to be completed by evaporation of the refrigerant in the heat exchanger where the heat conversion is carried out with the refrigerant or air[48]. When working on the refrigerant cycle, the final condensation link is also realized in the refrigerant or water heat exchanger inside the refrigerant, the heat generated by the refrigerant itself is completely absorbed through the working principle of the water circuit. Finally, the heat generated is transported to the soil through the water circuit. In general, the cooling of the house is done by using the cold air of 13-7℃[49]. The cooling is done mainly by means of a refrigerant-air heat exchanger, so that the heat in the room is continuously and steadily transmitted to the ground.

In the heating condition, to achieve work on the refrigerant, the compressor in the ground source heat pump unit must be borrowed to complete, while changing the direction of water flow, it is necessary to change the mode of water circuit switching to complete. Its working principle is: first use the underground water circuit circulation system to absorb the ground water or soil from the heat, and then evaporate, evaporation is the use of refrigerant or water heat exchanger within the refrigerant to complete, in the refrigerant cycle work[4], the heat generated by the refrigerant itself through the air circulation system, in the refrigerant or water heat exchanger after the refrigerant evaporated[50]. Generally, the heating of the house is done in the form of hot water of 35-50℃, so that the heat from the ground is continuously and steadily transferred to the room[9].

2.2 Application status and technical bottleneck of underground water source heat pump

The underground water source heat pump developed and utilized by the heat energy in the underground water body has higher efficiency than the ground source heat pump, and the system construction and operation cost are much lower than the ground source heat pump[51, 52]. Therefore, with the permission of hydrogeological elements, ground water source heat pump is preferred in practical application [53, 54].

2.2.1 Application and research status

As early as the end of 20th century and the beginning of this century, European and American countries began to pay attention to the environmental hydrogeological problems that may be caused by the operation of groundwater source heat pump system[55-57]. Although some environmental hydrogeological problems are speculative and have not been convincably demonstrated in practice, it is difficult to prove that such environmental hydrogeological problems will not be formed. Based on the need of cautious environmental protection, European and American countries have gradually stopped the construction of underground water source heat pump systems since the beginning of this century [57, 58].

In China, since the beginning of this century, researchers have gradually realized a series of problems caused by the construction and operation of the ground water source heat pump system[59, 60]. The problems summarized in the existing literature can be summarized as follows:

Table 2-4 Water source type heat pump working principle

existing problem	Main reason
The recharging efficiency decreased	The decrease of recharge efficiency [61-63] is caused by the gradual plugging of filter pipes due to the filling of fine particulate matter in aquifers or the precipitation and adsorption of substances in groundwater.
Well water quality variation	Corrosion of well wall pipe or pump water pipe leads to changes in well water quality [64, 65].
Thermal efficiency decline	Unreasonable design of mining density (high density).

As shown in Table 2-4, groundwater resources are lost due to reduced recharge efficiency. The fine particulate matter in the aquifer moves with the pumping to fill the filter pipe, which can be effectively prevented by extracting the aquifer medium sample and designing the filter layer according to the sample particle analysis in the process of hydrogeological drilling. If the filter pipe is gradually filled because of the precipitation and adsorption of substances in groundwater, because its role is limited to the well wall, targeted cleaning can be taken regularly, generally, it should avoid the decline in recharge efficiency. Well water quality variation, only because occurs in the wall pipe (including filter screen), water pump water pipe oxidation corrosion, completely can be properly taken in the design of anti-oxidation treatment (such as stainless steel screen screen, wall pipe using asphalt coating, pipe using appropriate coating, these measures are not only technically feasible and economic should also be within a reasonable range), Already built systems can be regularly cleaned, which can be effectively avoided. The decrease in thermal efficiency is mostly caused by the unreasonable design of mining density (high density), which can be completely avoided in the design stage[66].

Take the water-source heat pump heating project in Building 1 of Binhe Yujing Garden District as an example, in this energy-saving project, groundwater with a temperature of 9° C is pumped through a submersible pump and enters the side of the plate heat exchanger for heat exchange, and then re-injected into the same underground aquifer. At the same time, hot water is generated on the condenser side of the heat pump unit and delivered to the user side through the circulation pump heating system. The low-grade thermal energy resources contained in the groundwater resources are fully utilized in the project to promote the reform of the local heating mode.

With the emergence of global problems such as environmental pollution, resource destruction, desertification and "urban diseases" in today's world, human beings are becoming more and more deeply aware that they cannot blindly demand from nature, but should promote the construction of ecological civilization with a new economic development model to achieve the harmonious development of economic growth and the environment. The following is an analysis of the economic development in the construction of ecological smart city from the perspective of electric heating technology. The economic indicators of electric heating technology are the main indicators for the market to choose heating methods and technologies, including operation cost and initial investment. Operation costs, including energy costs, electricity costs, operation and management costs, labor maintenance costs, etc. Initial investment, i.e. the cost of construction of the heating system[67]. Among them, the heating energy cost is an important part of the system operation cost, which varies greatly with different fuels. Take the water source heat pump project in Building 1 of Binhe Yujing Huayuan District as an example. The annual saving of standard coal in this project is 298.5 tons. According to the current standard coal price of 800 RMB/ton, the annual cost saving of this project is 238,800 RMB. As a pilot project of electric heating, it shows with actual data that compared with the traditional centralized heating system, the electric heating system can save costs and bring considerable economic benefits, which achieves a high degree of consistency with the original intention of the Jilin Provincial Government to promote clean electric heating, effectively promoting the construction of an ecological and intelligent city, transforming the mode of economic development, and promoting the intensive use of resources and sustainable economic development[68].

For a long time, coal has dominated the energy sector in China. Due to the unusually cold and long winters in China's alpine regions, heating methods use coal as a fuel all year round, causing serious air pollution[69]. In Jilin province, for example, there are a large number of coal-fired boilers in the province, and these boilers have serious pollution problems during the winter heating period. Coal-fired boilers emit large amounts of pollutants during winter heating, which seriously affects air quality and endangers the health of residents. The construction of eco-smart cities promotes the evolution from a resource-depleted, environment-damaging real economy to a resource-saving, environment-friendly eco-economy. In order to improve the air quality of cities, the State Council has launched the "Air Purification Project". The use of clean energy sources such as electricity and natural gas, which produce significantly lower levels of nitrogen oxides and CO_2 and do not emit SO_2 , has greatly improved the quality of the atmosphere[70]. Electric heating and strengthening environmental protection transformation can not only greatly reduce the emission of environmental pollutants in densely populated areas, but also optimize the allocation of the carrying capacity of urban environmental resources, and also reduce the total emission of pollutants in energy consumption.

Table 2-5 No. 1 building water source heat pump project analysis

Expected benefits	economic indicators
Economic benefits	Annual savings of 298.5 tons of standard coal. According to the current standard coal price is about 800 RMB/ton. The annual cost savings for the project is about 238,800 RMB Energy saving rate reaches 50%
Social benifits	The annual standard replacement coal volume of this project is 297.6 tons The annual standard coal savings is 298.5 tons,and the energy saving rate is 50.8%
Enviormental benefits	CO2 emission reduction is 737.295 tons/year SO2 emission reduction is 5.97 tons/year

Dust emission reduction is 2.985 tons/year

2.2.2 Development constraint

At present, the application and research of underground water source heat pump system at home and abroad mainly focus on aquifers with large thickness (⩾10m), large depth (⩾50m) and small water-rich aquifers affected by atmospheric problems. Such aquifers are generally only distributed in areas where solute rocks develop or in alluvial and diluvial areas (mostly plain areas) where large loose layers develop [71-73]. Soluble rock and large thickness loose layer are often components of regional main aquifers. From the perspective of water resources and water environment protection, it is necessary to carry out research on the impact of the operation of the ground water source heat pump system on the target aquifer, which is the basis of the application of the ground water source heat pump technology[4].

Based on groundwater aquifers, aquifer burial conditions and groundwater hydraulic characteristics, Wang Nan [74]conducted a continuous study on groundwater quality variation caused by heat pumps on the basis of dynamic monitoring of groundwater quality in aquifers of existing project areas in Jilin Province. The average amount of surface water resources in Changchun for many years is 1.326 billion m^3, the available amount of surface water resources is 642 million m^3, and the available utilization rate of surface water is 48.4%. Data show that the amount of natural groundwater resources in Changchun city is $21773.8\times104m^3$/a. The average groundwater supply for many years is $22300.0\times104\ m^3$. Areas with abundant water resources in Changchun are selected as research objects, as shown in Table 2-6.

Table 2-6 Water resources in Changchun

Area	Recoverable capacity (m^3/d)	Remaining recoverable capacity(m^3/d)	Characteristics of water resources
Pore groundwater resources in Yitong Valley	68595.34	48853.0	Poor water quality, high iron and manganese content
Nanhu - Yitong River reach	16576.0	-0.123	Annual water level variation of about 20m, uneven recharge capacity
Xinglonggou section	30904	19254	Salinity less than 0.8g /L pollution-free
Four rooms. - A small town	-	-0.0312	Salinity less than 0.8g /L pollution-free

Table 2-6 shows that in the pore groundwater of Yitong River Valley, the water-rich areas are distributed in the Yitong River Valley region, and the water-rich areas are distributed in a ribbon on the west side of the rich area. The aquifer features are similar to the above, except that the sand and gravel thickness become thinner and the grain size becomes finer [75]. As the suitable conditions for water source heat pump, the amount of water resources can meet the requirements, the amount of remaining resources is more, but the water quality is poor and the content of iron and manganese is high. In addition to the water quality, the recharge condition is better, and the burial depth is shallow. The bedrock groundwater resources of Jiajiawzi-Xinglonggou are distributed in the area of Jiajiawzi-Xinglonggou, the lithology is hard and brittle, and the fractures are developed. In the Nanhu to Yitong River section, the groundwater overexploitation phenomenon is serious, and the amount of remaining resources is very small, so the water resources developed by the water source heat pump system will be difficult to meet. Sijianfang-xiaozhengzi groundwater resource area is distributed in the Sijianfang-Xiaozhengzi area along the northeastward direction. The aquifer is composed of calcaly-rich siltstone and silty mudstone of the Nenjiang Formation, with developed fractures and scarce remaining resources. The water requirement of the water source heat pump system is difficult to meet, but the underground water quality in this area is good and the burial depth is deep [76]. There is only 20000 m3/d of residual water resources in Xinglong Valley section of bedrock groundwater. At the same time, the groundwater in this area is very suitable for hydrothermal development in winter. Therefore, an increased proportion of surface water extraction should be used, and more groundwater should be used for heating in order to maximize energy use. And then achieve the purpose of saving energy and protecting the environment.

Monitoring Wells are set up in the relevant waters to test the water quality. Areas with higher hardness and more iron ion content will have an impact on the underground water source heat pump, which may lead to the formation of scale blocking pipes and seriously affect the working efficiency of the water source heat pump. Therefore, the higher the hardness value, the more iron ion content, the lower the corresponding value. as shown in Table 2-7. The hardness of observation Wells 26001056 and 26000061 can meet the requirements (<200mg/L), but the hardness value of most areas is more than 200mg/L, which cannot meet the requirements of the establishment of water source heat pump, and the value should be small. All Fe3 + were less than 1 mg/L, which could meet the requirements. In addition to the observation well 26001056, which can meet the requirements in terms of salinity (<300mg/L), most areas cannot meet the requirements for the establishment of water source heat pump. The high salinity and hardness content is easy to lead to the blockage of the water source heat pump system, and the late operation of the system will affect the strength of the recharge capacity[77].

Table 2-7 Observe well water chemical index

Serial number	Observation well	position	Salinity (mg/L)	Total hardness (mg/L)	Fe^{3+}（mg/L）
1	26000207	Yangjia Tun	776	314	0.09
2	26000108	20 Tiebei Road	1559	393	0.15
3	26000019	Lihin Bath	904	286	0.34
4	26000230	Xinglong Mountain Town	648	212	0.21
5	26000031	Dannan town	592	259	0.15
6	26000033	Yongchun township	1150	505	0.01
7	26000034	Hexin town	592	314	0.05
8	26000339	Yutan town	462	238	0.53

9	26001056	Geological school	179	112	0.08
10	26000061	People's Street City	464	200	0.68
11	26001064	North seventh Street	791	339	0.06
12	26000267	Xixin township	540	268	0.07

In general, the groundwater source heat pump system needs to extract groundwater. From the perspective of water resources and water environment protection, the groundwater extracted is generally required to be recharged in the same layer and in the same amount after heat exchange. At this point, for the construction and operation of the underground water source heat pump system, the main constraints are unavoidable[78]:

(1) In the recharge process, oxygenation in water bodies is inevitable; The operation characteristics of the heat pump system determine that there are more aeration opportunities and the aeration effect is strong. Aerated (i.e. oxygenated) water recharging into aquifers (groups) in a reducing environment will result in oxidation reactions of some NH4 +, Fe 2+, NO2 - plasmas; As a result, the groundwater quality has a certain degree of variation, and this variation occurs in a certain range of water-bearing layers. The variation of water quality in aquifers may have a lasting impact on the safety of groundwater quality.

(2) Under specific hydrogeological conditions, the operation of the heat pump system may cause serious variations in water quality due to changes in seepage velocity and recharge conditions. In order to determine the feasibility of project construction and operation, it is necessary to deeply study the change of hydrogeological conditions under the operation conditions of heat pump system and its influence on water quality.

(3) Water quality changes induced by water temperature changes in aquifers and sustainability of recharge efficiency also form certain constraints on the construction and operation of subsurface water source heat pump system.

2.3 GSHP application status and technical bottlenecks

As mentioned above, the development and application of groundwater source heat pump is not only affected by the uneven distribution of groundwater sources, but also has a certain impact on the quality of groundwater, which leads to a greater constraint on the application of groundwater source heat pump[17]. During the operation of the ground source heat pump system, the circulating working medium inside the closed circulation tube only exchanges heat with the rock and groundwater outside the tube wall, i.e. the working medium does not come into direct contact with the surrounding rock and soil body. Therefore, ground source heat pump system has become the main way to apply shallow geothermal energy for building heating and cooling[7].

2.3.1 Application and research status

Because the underground heat exchanger with the geotechnical body and the underground body of water heat exchange, is buried in the ground to a certain depth of the pipe constituted, so the underground heat exchanger is also known as underground buried pipe heat exchanger. 1946, the United States in the downtown area of Oregon's Polite built 12 horizontal buried pipe ground source heat pump system, and the project as a research example, began to buried pipe size (pipe diameter), pipe spacing and buried depth and other buried pipe In1953[79], the American Electric Power Association (electric utility committee) considered that the above experimental results still could not provide a calculation method for design use. Britain and other European countries, also in the 1950s, relying on residential heating 30 engineering examples, to carry out related technical applications and theoretical research; to the 1950s, Europe and the United States have nearly 10,000 (only Sweden has built 6,000) engineering examples, the above examples of heat transfer pipe is mainly horizontal buried form.

With the support of the U.S. Department of Energy (DOE), Oak Ridge National Laboratory (Oak Ridge National Laboratory) [80] [81, 82]and Brookhaven National Laboratory (Brookhaven National Laboratory)[83, 84] and other universities and research institutes such as Oklahoma State University [85-88] and other universities and research institutes, concentrated on researching the underground heat exchanger heat transfer characteristics of ground source heat pump systems, soil thermal properties, comparison of the performance of different forms of buried tube heat exchangers, and carrying out various forms of underground buried tube heat exchanger installation and testing[29].

In 1998, the U.S. Department of Energy (DOE) did require the promotion of soil-source heat pump systems in federal government agency buildings and imposed certain conditions of use[89]. This was part of an effort to encourage the adoption of more sustainable and energy-efficient heating and cooling technologies[90]. Since then, the use of ground-source heat pumps (also known as geothermal heat pumps or soil-source heat pumps) has been steadily growing in the United States. As buildings have expanded in size, more installations of ground source heat pump systems have occurred. The average annual growth rate of their use has been above 15%, indicating a growing trend in the adoption of such systems[91].

Ground source heat pumps are also used quite widely in Europe, especially in the Nordic countries. Nordic countries, such as Sweden, Norway, Finland, Denmark and Iceland, have been at the forefront of promoting and implementing sustainable energy solutions. Due to their colder climates, ground source heat pumps offer an efficient and reliable method of heating and cooling buildings, making them an attractive option for these regions[92]. Overall, the growing use of ground source heat pumps in the United States and Europe reflects the recognition of their energy efficiency, environmental benefits, and long-term cost savings compared to conventional heating and cooling systems[25].

The application and research of ground source heat pump technology in China began in 1995[93]. 1995, the Chinese Ministry of Science and Technology and the U.S. Department of Energy signed the "Sino-U.S. Department of Energy Agreement on Cooperation in the Field of Efficiency and Renewable Energy Technology Development and Utilization"[94], and in 1997, they also signed the "Sino-U.S. Protocol on Cooperation in Energy Efficiency and Renewable Energy", in which the two governments included ground source heat pump air conditioning technology into the scope of cooperation[95]. 1998, the Domestic universities and colleges, scientific research institutions and related enterprises cooperated with each other and began to conduct applied theoretical research and practical application promotion[96].

2.3.2 Technology Development Process

The history of changes in ground source heat pump heat exchanger structure and burial method, heat exchanger tube material, and heat exchanger tube external filling material, etc[97]. Ground source heat pump technology has undergone a relatively long evolution in practical application[25].

(1) Heat exchanger tube material

In the early days of ground source heat pump technology, metal pipes and horizontal burial methods were primarily used for the heat exchange pipe systems[98]. However, the high cost, difficult installation process, and susceptibility to corrosion made it challenging for ground source heat pump technology to be widely adopted.

The development of polyethylene (PE) and other plastic pipe technologies played a crucial role in advancing ground source heat pump applications. In 1988, the International Gas Union (IGU) gas distribution committee recognized the benefits of using polyethylene pipes for buried gas pipelines, including reliable quality, safe operation, easy maintenance, and low cost[99]. Drawing from the experience and technology of buried gas pipelines, ground source heat pump researchers and practitioners started replacing metal pipes with PE pipes for underground heat exchange.

PE pipes offer several advantageous characteristics[100]. They can be connected through hot fusion and electric fusion methods, achieving integrated interfaces and pipelines. They are durable and can last over 50 years under specified temperature and pressure conditions. PE pipes have excellent pressure resistance, toughness, and high impact strength, ensuring they don't rupture even when subjected to heavy loads[101]. They are also considered environmentally friendly and hygienic since they are made of non-toxic materials, resist scaling, and do not promote bacterial growth. Additionally, the construction of PE pipes is relatively easy and cost-effective, with light weight, simple welding processes, and overall lower project costs.

As a result of these advantages, PE pipes have become the predominant choice for underground heat exchange systems in ground source heat pump applications worldwide. The commonly used outer diameter of these pipes ranges from φ25mm to φ35mm, with a working pressure capacity of 1.0Mpa to 1.6Mpa and a working temperature range of -20℃ to 40℃[102].

(2) Filling material and filling method

The filling material used in ground source heat pump systems refers to the material that is placed between the heat exchanger tube and the surrounding ground[103]. Its primary roles are to securely fix the heat exchanger tube in the buried position and to create a continuous solid medium around the tube, thereby enhancing the heat exchange efficiency between the tube and the ground. Currently, the most common practice is to backfill the space around the heat exchanger tube directly with excavated rocks, soil, drilling chips, and mud generated during the drilling process. In some cases, additional materials such as bentonite may be added to improve the thermal conductivity of the backfill material. However, regardless of the specific composition, the filling material is typically in an unconsolidated and loose state, meaning it lacks significant compaction or consolidation[104].

This loose filling mode is commonly employed because it allows for efficient heat transfer between the heat exchanger tube and the surrounding ground. It helps to maximize the contact area between the tube and the ground, facilitating the exchange of heat energy. Additionally, the loose filling material allows for flexibility and accommodates any potential ground movements without causing damage to the system[105].

It's worth noting that the choice of filling material and its proper installation are important factors in ensuring the long-term performance and efficiency of a ground source heat pump system. The specific requirements and recommendations for filling materials may vary depending on local regulations, geological conditions, and project specifications.

(3) Heat exchanger tube burial method

The two main forms of buried pipe heat exchangers used in ground source heat pump systems are horizontal buried pipes and vertical buried pipes[106].

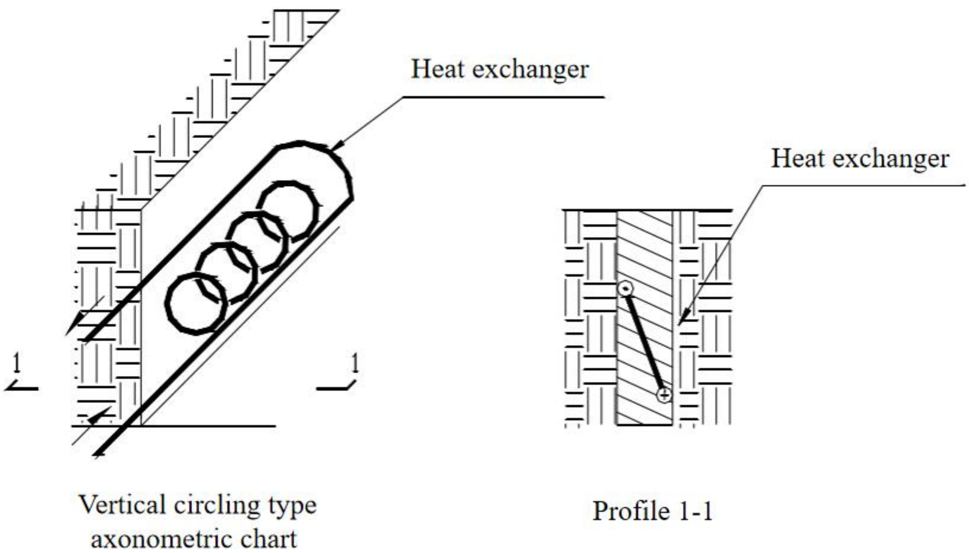
Horizontal buried pipe heat exchanger: The horizontal buried pipe heat exchanger was one of the earliest forms of buried pipe heat exchange systems used in soil source heat pumps[106]. It consists of pipes buried horizontally in the ground. There are several variations of the horizontal buried pipe heat exchanger, including single-layer, double-layer, and multi-layer configurations. The pipes can be installed in a vertical row, horizontal row, or even in a horizontal spiral pattern.

In terms of construction and economic considerations, it is generally recommended to bury the horizontal pipes at a depth of 1.2 to 1.5 meters. This depth provides optimal heat exchange with the surrounding ground. If the burial depth exceeds 1.5 meters, slope protection facilities may be required during the trench construction, which can significantly increase the overall construction costs.

Vertical buried pipe heat exchanger: The vertical buried pipe heat exchanger involves installing pipes vertically in boreholes drilled into the ground. This method is typically used when space is limited or when the soil conditions are not suitable for horizontal installations. Vertical buried pipe heat exchangers are more common in areas with denser urban environments[107].

In this configuration, the pipes are installed in a straight, vertical orientation, and they extend to a considerable depth depending on factors such as soil properties and the heat pump system's requirements. The vertical arrangement allows for efficient heat transfer between the pipes and the surrounding ground.

Each of these buried pipe heat exchanger configurations has its advantages and considerations, and the choice between them depends on factors such as available space, soil conditions, cost considerations, and project requirements.



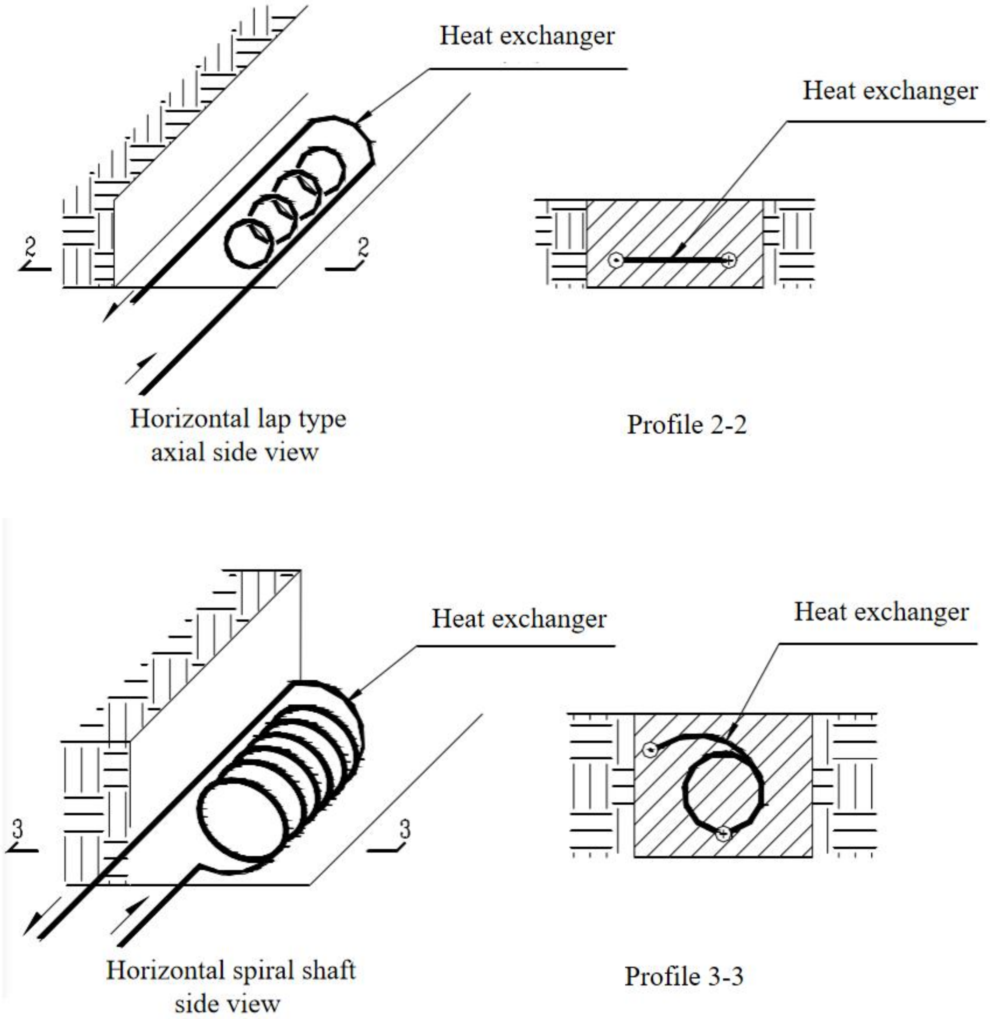


Fig 2-4 Form of horizontal ground heat exchangers [108]

The literature on the efficiency and calculation methods of horizontally buried heat exchanger tubes was more prevalent before the 1980s[109]. However, since the 1990s, such literature has gradually decreased and become rare.

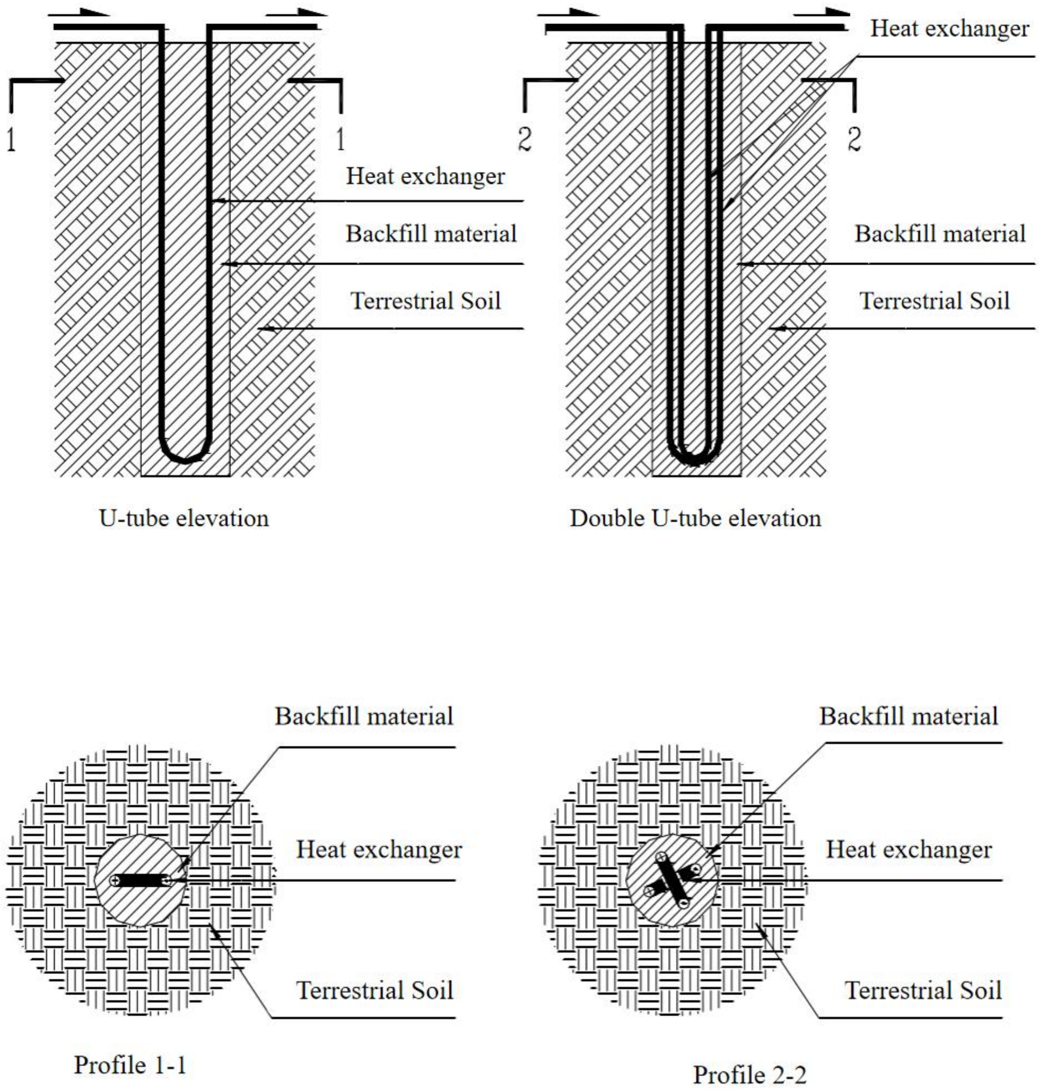
Oklahoma State University's research report provides detailed experimental and calculation procedures for heat exchangers using PE tubes with diameters ranging from φ20mm to 32mm, laid in straight pipes[110]. The report focuses on horizontally buried heat exchanger tubes with shallow burial depths, which offer convenient construction and relatively low installation costs. However, these configurations have lower heat transfer efficiency and require a larger surface area due to their exposure to environmental temperatures.

As a result, the use of horizontally buried heat exchanger tubes has gradually reduced, and the current trend favors vertical buried forms. The vertical buried tube heat exchanger consists of a group of underground heat exchange pipes that can be buried in vertical boreholes in the ground or in concrete pile foundations. This configuration has a smaller footprint compared to horizontal installations.

In a vertical buried tube heat exchanger, the tubes are surrounded by backfill material, and the fluid inside the tubes undergoes heat exchange with the tube walls, backfill material, and surrounding soil. The backfill serves to enhance heat transfer, seal the system, and prevent groundwater contamination from surface water infiltration. Different configurations of vertical buried tube heat exchangers include single U-type, double U-type, spiral type, and casing type[111].

In the mid-1980s to mid-1990s, dozens of combined heat and cold ground source heat pump projects were constructed in the United States and Canada, with a majority of them utilizing U-type vertical buried tube heat exchangers[112]. The borehole diameter for the common engineering vertical U-shaped buried pipe heat exchanger is generally between 70-200 mm, with borehole depths ranging from 30-150 m[113]. These depths are relatively small compared to the depth of the buried pipe itself.

Table 2-8 provides information on the performance and application range of three different forms of heat exchangers: U-tube type, double U-type, and casing type[114].



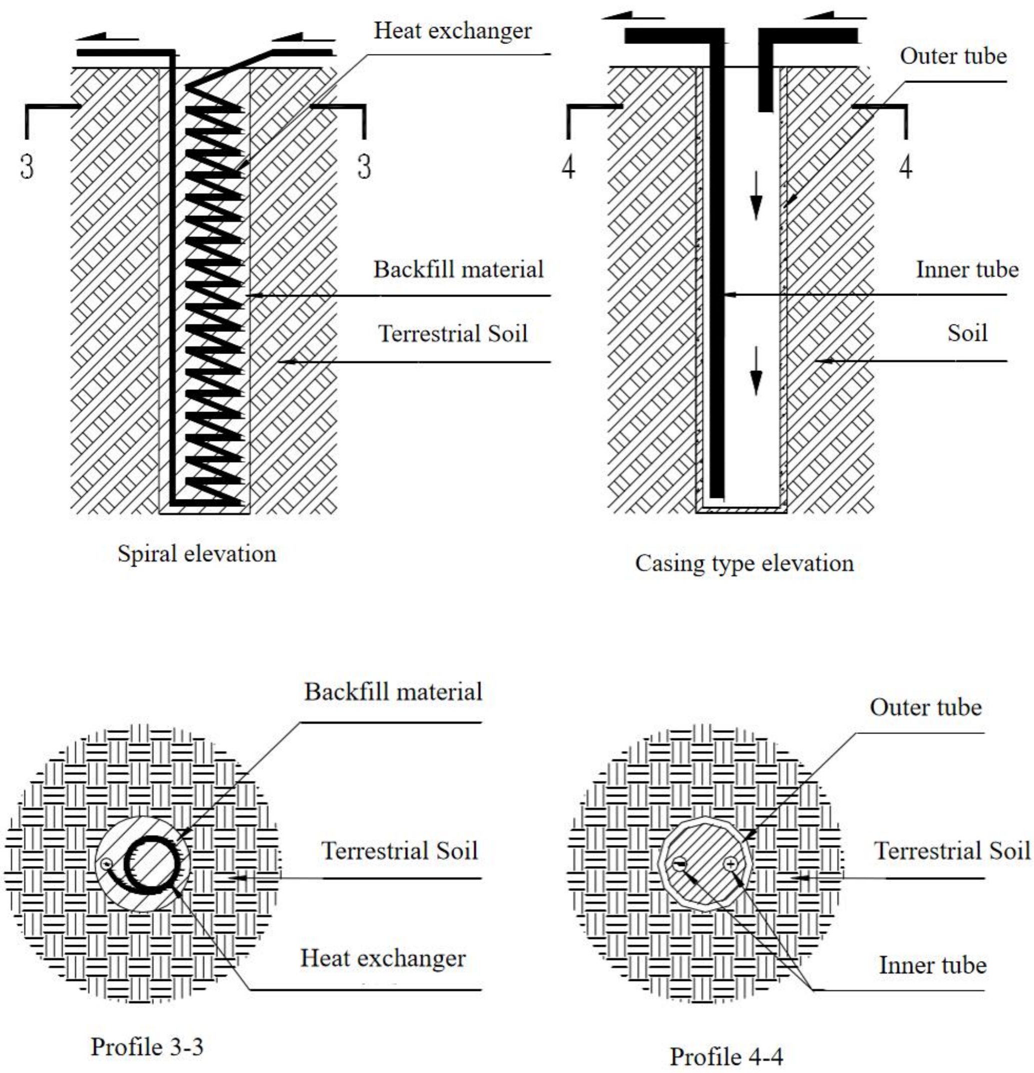


Fig2-5 Form of vertical ground heat exchangers[115]

Table 2-8 Heat exchanger performance characteristics and scope of application

Heat exchanger type	Features	Scope of application
U-tube	High reliability, strong pressure-bearing capacity, low construction difficulty, small borehole diameter, deeper burial, etc.	Deeper burial vertical buried pipe method
Double U-tube	Heat transfer efficiency can be increased by 10~15% compared to single U type heat exchanger with the same size drilling.	Reduce floor space and improve heat transfer efficiency
Casing type	High heat exchange rate, high heat loss, diameter of the borehole, difficult construction, etc.	The vertical buried pipe method with shallow burial depth

Yupeng Wu et al[116]. conducted experimental measurements of a horizontally coupled spring-loaded ground source heat pump system at Talbot Lodge, St Leonard's site, Drayton, Oxfordshire, UK, using a CFD model to measure the thermophysical properties of the in situ soil. Using the validated 3D model, the thermal properties of a horizontally coupled spring-loaded ground source heat pump system with different coil diameters and spring spacing distances were investigated. The thermal performance of spring heat exchangers with different coil diameters and spring spacing distances in a horizontally coupled ground source heat pump system was investigated using a validated 3D model. After two months of monitoring the performance of the ground source heat pump system, the results showed that the COP decreased with increasing operation time. The average COP of the horizontally coupled ground source heat pump system was 2.5. The numerical predictions indicated that there is no significant difference in the specific heat extraction of the spring heat exchanger with different coil diameters. However, the larger the diameter of the coil, the higher the heat extraction per meter of soil length[117]. The specific heat extraction also increases, but the heat extraction per meter of soil decreases as the distance between the centers of the coils increases.

Selamat et al[118]. investigated the use of different layouts and pipe materials to optimize the horizontal ground heat exchanger design, CFD simulations of the 3D model were performed and thermodynamic comparisons were made, and the results showed that by using materials with higher thermal conductivity, heat build-up within the pipe walls could be retarded, and copper pipes were 16% more effective than polyethylene plastic pipes, and when the heat exchanger was reasonably installed The effective heat transfer rate in the vertical direction is 14% longer than in the horizontal direction, and over time ,The thermal interference effect diminishes as heat builds up on the ground, but further improvement in the vertical direction is expected when the heat flow between the connected pipes interacts. Finally, factors such as heat pump load, time of use and available resources should be weighed to achieve a good balance between system efficiency and system cost effectiveness.

Although the vertical buried pipe heat exchanger drilling depth is larger, buried costs are higher, but because the system occupies a small area, heat transfer is not easily affected by the climate, unit buried area heat exchange, etc., in the ground source heat pump project is widely used.

2.3.3 Technical Advantages

Ground source heat pump uses soil as the heat absorption and exhaust site of the heat pump unit. According to research, the temperature of the soil at a certain depth underground basically does not change with the external environment and seasonal changes, and is approximately equal to the annual average temperature, which can provide suitable evaporation and condensation temperatures for winter and summer. Compared with air-source heat pumps, soil-source heat pump system units are noiseless and do not require defrosting[119]. Compared with water source heat pumps (groundwater and surface water), they are not limited by the geographical location of water resources. Soil source heat pump has good energy saving performance and stable performance, and its technical advantages are as follows:

Ground source heat pump system resources clean and renewable. Ground source heat pumps utilize shallow geothermal energy stored in the earth's surface, which stores 47% of solar energy (nearly unlimited renewable clean energy), making them independent of any geographical or resource constraints[120].

Ground source heat pump systems are highly efficient and energy saving. Underground soil temperature is relatively stable year-round, making it an ideal source of heat pump heat and air conditioning cooling. According to the US EPA, ground source heat pumps can save 30%-50% of the heating and air conditioning operating costs[121]. High efficiency ground source heat pump units save 30%-60% of electricity consumption than traditional cooling and heating methods (ordinary chiller + boiler centralized air conditioning)[122].

Ground source heat pump systems have good environmental benefits. Ground source heat pump system uses the solar energy stored in the soil, no combustion, no smoke emission. The amount of refrigerant (Freon) is low, with a 25% reduction in charge and a low refrigerant leakage rate compared to conventional air conditioners[45]. Compared with air-source heat pumps, ground-source heat pumps have no noise and thermal pollution, and emissions are reduced by 40%.

Ground source heat pump systems do not occupy building space[123]. The heat capacity coefficient of the geotechnical body is smaller than that of water, and although a ground source heat pump system requires a larger heat exchanger under the same heat exchange conditions, the heat exchanger of the ground source heat pump is located in the garden, lawn or under the building, and does not occupy the above-ground space of the building.

2.3.4 Technology Bottlenecks

The development and utilization of ground source heat pump technology have had a significant impact in Europe, the United States, and China[60]. While the technology originated in Europe in the 1970s and has been extensively developed and applied in Europe and the United States, it was introduced and applied in China at the end of the last century[124]. However, in China, the direct application of ground source heat pump technology developed in Europe and the United States is greatly restricted due to factors such as building volume ratio and other conditions specific to the country. Nonetheless, ground source heat pump air conditioning systems in China typically consist of three main components: the outdoor ground temperature energy exchange system (vertical type heat exchanger), the heat pump units, and the indoor air conditioning end system.

Currently, the manufacturing technology of heat pump units and the indoor end system is relatively mature, and the differences in quality among manufacturers are not substantial[125]. The installation of heat pump units and the construction of indoor end systems do not pose significant technical challenges, and general contractors have the necessary technical expertise. However, the core aspect that determines the reliability, safety, and overall efficiency of ground source heat pump air conditioning systems lies in the construction level and heat exchange efficiency of the vertical type heat exchanger, also known as the underground heat exchange system.

In the development and utilization of geothermal energy through ground source heat pumps, there are certain advantages and disadvantages. Some of the main technical bottlenecks or challenges include the following:

(1) High number of drilling holes, large footprint and high cost

Take the residential area of Nanpingjiayuan at the intersection of Wangxi Road and Dongzhi Road in Shushan District of Hefei City as an example[126]. In Hefei area, the annual average temperature is 15.5 ℃, the stratigraphic zoning belongs to North China stratigraphic region Jin, Hebei, Lu and Yu stratigraphic zone South China margin stratigraphic subzone, the surface loose strata are generally more developed, the thickness is mostly about 20m; in the depth range of 20~200m, the ground temperature is about 17.5℃.

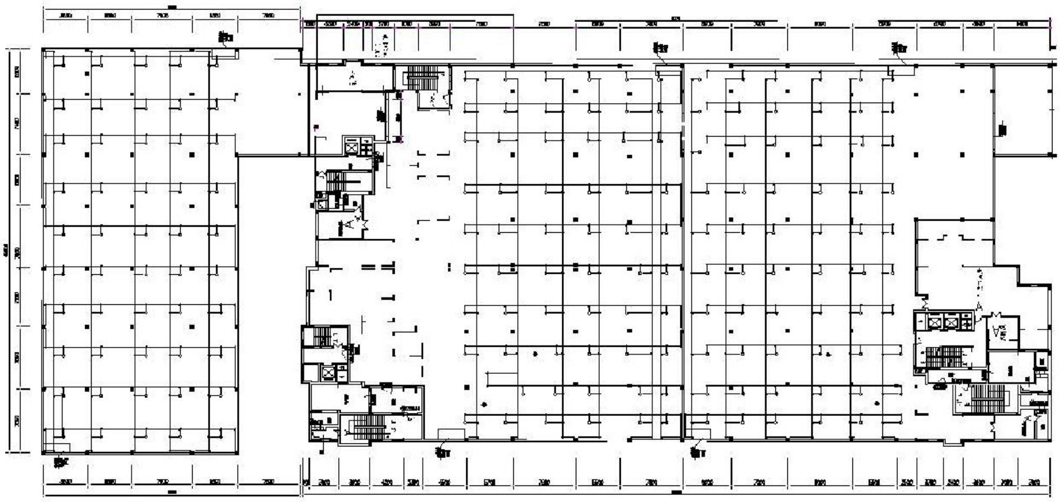


Fig2-6 Floorplan for heat transfer drilling about Nanping garden in Hefei City[126]

The building type is high-rise general residential; the total area is about 19,000m^2, the volume ratio is 3.38; the total area of the building is 73,000m^2, the area of the building with ground source heat pump is 46,000m^2, and more than 600 boreholes with 120m depth and 150mm diameter are designed (Fig2-6), the hole spacing is 5m, and the total area of the borehole is 12,000m^2. The building area of 46,000m^2 requires More than 600 holes, which is equivalent to 1 hole/130m^2 building; the plot covers 19,000m^2 and the borehole covers a total area of 12,000m^2, 63% of the area within which the borehole is to be built. The reason for more boreholes is the low heat transfer efficiency of boreholes, which in turn leads to high construction cost and large floor space.

(2) PE pipe damage is difficult to repair

The circulating fluid hose (mostly PE pipe) is buried deep in the borehole, which is filled with loose materials such as silt or mud, so once the circulating pipe is damaged, it basically cannot be repaired in-situ. The borehole is mostly filled with loose material, and in actual construction, the mixture of drilling rock chips and mud is filled directly into the hole (the so-called original slurry backfill); once the solid particles are deposited, the PE pipe (circulation pipe) cannot be pulled up or relocated to the borehole once it is damaged; therefore, it is basically difficult to carry out repair treatment. Restricted by drilling conditions, many boreholes near buildings and boreholes covered by buildings, cannot be re-drilled on the original hole location; even if there is a position to fill the hole, the new fill hole and the original system is difficult to achieve hydraulic balance, that is, the addition of new fill hole, because of hydraulic imbalance so that the new fill hole over water is not enough (or new fill hole interference, so that the original system in part of the hole over water is not enough) and lead to hole heat transfer efficiency cannot reach The design requirements.

(3) Environmental pollution

The current ground source heat pump technology, basically is the use of loose filling (because the circulation pipe for PE pipe, using solidification filling, filling in the process of solidification, may be the circulation pipe "hold"); loose material filling of the borehole, the formation of ground rain and sewage infiltration channel (although the orifice often also take measures to close, but because of the ground and the closure of the material cannot be fully integrated and construction quality problems, etc., the orifice still have infiltration of pores and fissures); When the borehole is uncovered through different aquifers, the water quality of different aquifers differs, and the loose-filled borehole forms a "string layer pollution" channel for different aquifers. It is worth pointing out that some domestic construction enterprises, in the construction process, treat drilling mud and rock chips as filling In addition, the drilling process, in order to adjust the performance of the mud, generally add more chemical agents, this mixed in the mud chemical agents, will be slowly released under the action of the seepage, to the aquifer The groundwater and the geotechnical environment around the borehole pose a serious pollution hazard.

(4) Safety hazards

The lower part of the building and the surrounding densely placed holes, drilling more than the depth of the foundation, drilling disturbance and drilling cavity through the impact on the foundation structure, to the building safety formed a hidden danger[127]. The design of the foundation of the building, mostly before the design of air conditioning, the design and construction of the heat pump underground heat exchange borehole, often without fully considering its impact on the foundation bearing layer; When the number of boreholes is large, the drilling of disturbance to the ground, loose material filled boreholes, will be on the building foundation safety, forming a serious hidden danger.

Still take Hefei Nanping home residential district as an example. Build more than 600 holes of 100m deep and 150mm diameter holes, drilling covers a total area of 12,000m^2; the plot covers a total area of about 19,000m^2, so it can only be arranged around the foundation as well as under the building. The engineering measurements based on which the building foundation was designed did not take into account the influence of these holes on the foundation; the drilling increased the void rate of the foundation by 6% (0.15m/2.5m), and the proportion of the foundation bearing layer was disturbed by up to 20% (based on the drilling disturbance radius of 0.5m, the disturbance proportion = 0.5m/2.5m); with such a large influence, the ground source heat pump heat exchange holes should have some influence on the building safety under the condition that the foundation is not reviewed. construction should have certain safety hazards for building safety.

2.3.5 Technology Bottlenecks in cold regions of China

According to the relevant data, the projects using soil source heat pump systems in China are mainly distributed in cold regions and hot summer and cold winter regions[7, 128], but the actual projects applied in cold regions are less, which is due to the special climatic characteristics of cold regions, the heat load required in winter is greater than the cold load required in summer, resulting in the heat absorbed by the system from the soil in winter is greater than the heat discharged to the soil in summer, and the soil will have cold buildup, which is the key reason limiting the development of soil source heat pumps in cold regions. At the same time, because ground source heat pump systems require drilling wells underground, which costs more, about 50% of the total cost, some people believe that the initial investment is much higher than traditional air conditioning methods, but ignore the economic benefits of ground source heat pump systems in long-term operating conditions. Currently, there are other problems with ground source heat pumps as follows:

The development of soil source heat pump systems in China is mainly concentrated in cold regions and hot summer and cold winter regions. However, the application of these systems in cold regions is limited due to the specific climatic characteristics. In cold regions, the heat load required in winter is greater than the cooling load required in summer. As a result, the heat absorbed by the system from the soil in winter exceeds the heat discharged to the soil in summer, leading to a buildup of cold in the soil. This imbalance hinders the development of soil source heat pumps in cold regions.

One challenge with ground source heat pump systems is the high cost of drilling wells, which accounts for about 50% of the total cost. Some people consider the initial investment of ground source heat pump systems to be higher than traditional air conditioning methods, but they overlook the long-term economic benefits of these systems in terms of operating conditions. There are several issues related to ground source heat pump systems:

GSHP system field testing issues: The lack of relevant national standards for testing is a major problem. It is unclear which operating conditions of the soil source heat pump system should be simulated during testing and how the heat transfer data per linear meter should be corrected for system design. Additionally, determining the heating and cooling power of the test apparatus and the water flow rate in the buried pipe heat exchanger poses challenges.

GSHP system design issues: Currently, two main methods are used for designing the buried tube heat exchanger of soil source heat pump systems. The dynamic composite simulation design method is more accurate, while the heat exchange per linear meter method has limitations and should only be used during the program design stage.

GSHP system construction quality control and testing issues: The construction quality of the buried pipe heat exchanger system significantly impacts its heat transfer efficiency. Some builders may take shortcuts to save backfill materials and expedite the drilling process, which can lead to difficulties in backfilling and inadequate compaction. The use of mechanical backfill, as recommended by engineering specifications, is limited, and natural slurry backfilling is more common but may have hidden quality problems.

Practical operational issues of GSHP: Despite manufacturers promoting the benefits of heat pumps, there are practical challenges during operation. These include unstable supply and return water temperatures on the ground source side, low performance coefficients of the unit and system energy efficiency, and a potential drop in indoor temperature over time.

GSHP heat balance problem: In cold regions, the heating demand outweighs the cooling demand, resulting in an unbalanced heat extraction from the underground soil. This can lead to the accumulation of cold in the soil over time, affecting the service life of the system and the thermal and ecological environment of the soil. The imbalance in soil temperature can also decrease system efficiency and have ecological and geological impacts.

The thermal imbalance caused by ground source heat pump systems can affect the activity of biological enzymes, change the microcirculation of underground temperature, impact the diversity of ecological species, and influence the migration of soil salt. It can also have irreversible impacts on the natural environment, including the hydrological environment, site environment, and groundwater cycle. These challenges highlight the need for further research, standardization, and quality control measures to overcome the limitations and maximize the benefits of ground source heat pump systems in China.

2.4 Literature review of the operational performance of GSPHs

Ground source heat pump (GSHP) systems have proven to be highly efficient and effective in reducing space heating and cooling energy consumption in buildings compared to conventional air source heat pumps (ASHPs). GSHP systems utilize the ground as a heat source during the heating season and expel heat to the ground during the cooling season, resulting in energy transfer from the conditioned space to the ground. This technology takes advantage of the relatively constant temperature of the soil, ensuring system stability and high efficiency. Research studies have demonstrated the performance and benefits of GSHP systems in various settings:

Zhai and Yang [129] conducted a study on a GSHP system installed in an archive in Shanghai. The system achieved an average coefficient of performance (COP) of 4.7 in summer and reduced cooling power consumption by 56% compared to a conventional ASHP.

Ally et al[130] tested a 2.16-ton GSHP in a residential building in Oak Ridge, Tennessee. The GSHP was able to meet the entire space cooling load with maximum and minimum COPs of 5.16 and 3.72, respectively.

Naili et al[131] tested a GSHP in a hot climate in Borj Cédria. The system successfully met the cooling load with an average heat pump COP of 4.5 and system COP of 3.

Mohamed et al [132] monitored the cooling performance of GSHP systems in two single-family houses in Canada. The GSHP systems achieved high performance factors, with COPhp values of 12.9 and 11.0 for seasonal heat pumps and GSHP systems, respectively. The total electricity consumption and operating costs of the GSHPs were 66% lower than those of conventional air conditioners.

Rong Hu et al [133] investigated a hybrid recovery GSHP system combined with thermally activated building systems (TABSs). The system achieved a COP of 5.49 and exergy efficiency of 16%. The integration of cooling towers helped limit the condensate temperature below 40°C, enhancing operational performance.

Rongsheng Liu et al[134] conducted a comprehensive review of GSHPs' energy efficiency. They found that installation depth, unit specifications, system configuration, and operational mode influence the energy efficiency of GSHPs. Additional components and improved materials, such as nanofluids, can enhance efficiency.

Hansani Weeratunge et al[135] evaluated the economics and optimal sizing of solar-assisted GSHP (SAGSHP) systems in various climates. SAGSHP systems were found to be cost-effective in locations with high solar irradiation, electricity prices, and gas prices, with potential savings of 30%.

Jingmeng Sang[136] explored the factors affecting the efficiency of GSHP systems in cold regions. Discrepancies between design expectations and actual operation were analyzed, highlighting factors such as water temperature, leakage, insufficient well depth, and fouling concentration.

Hongzhi Zhang et al [137] analyzed the annual performance of GSHP systems using a three-dimensional dynamic simulation platform. They found that reducing soil moisture transfer radius, icing time, and icing distance while increasing pipe spacing improved unit performance.

Liang Pu et al [138] investigated the thermal and pressure performance of vertical U-tube GSHPs numerically. They found that increasing the Reynolds number and tube diameter under laminar flow conditions resulted in better overall performance. Parallel U-tube configurations provided higher heat flux and lower pressure drop.

The advantages of GSHP systems, such as stability, efficiency, and cleanliness, have led to increased adoption in public and civil buildings. However, further research is needed to address remaining challenges and improve system performance.

2.5 Literature review of the heat balance of GSHPs

Ground source heat pump (GSHP) systems have a longlife expectancy of 20 to 40 years[135]. However, long-term operation without balanced annual heat extraction and rejection can gradually affect the underground soil temperature, leading to reduced system performance and efficiency[32]. Zhu et al. proposed increased borehole spacing as a solution to mitigate soil thermal disturbance and extend the system's operating life [139]. In urban areas with limited space for ground heat exchanger (GHE) installation, a suggested distance between boreholes is 4-5m [140]. However, increasing hole spacing limits the application of GSHP systems and reduces their economic benefits due to the large underground heat exchanger area.

To reduce land usage, some projects have placed GHE in building pile foundations, but this approach makes maintenance more challenging [141]. Moreover, in regions with cold winters, achieving complete balance between cooling and heating loads is challenging [51] [53]. Long-term operation in such areas results in soil thermal imbalance and decreases the system's coefficient of performance (COP) [104, 142, 143].

Several studies have monitored the performance of GSHP systems over extended periods. For instance, Luo et al.[144] tested the cooling performance of a GSHP system installed in an office building in Nuremberg, Germany, over four years. The heating load was four times greater than the cooling load, leading to an annual increase of up to 8.7% in cooling performance and a decrease of up to 4% in heating performance.

In a study by Michopoulos et al. [145], a GSHP system installed in a New Municipality Hall in Greece was monitored and evaluated over eight years. The system, including 21 boreholes with a spacing of 4.5m, achieved a COP of 4.5 under cooling operation, reducing CO2 emissions by up to 22.7% compared to conventional air-source heat pump systems. Notably, the COP during the eighth year was nearly the same as the first year, indicating the system's ability to maintain efficiency in the region's climate.

The impact of a vertical GSHP system on ground temperature was assessed by Montagud et al.[146] in a 250 m2 office building at Polytechnic University of Valencia. Over five years, with six boreholes spaced at 3m, the outlet water temperature from the ground loop remained constant at 17°C between February 2005 and February 2010.

In a study by Xi et al. [147], the heating and cooling performance of a vertical GSHP system in a 4,449 m2 office building was evaluated over two years. The system, comprising 201 boreholes and two heat pumps, achieved average daily COPs of 5 for heating and 3 for cooling. The operation of the GSHP system led to a ground temperature increase of 1.1°C after two years.

Proper borehole layout and contact area with the surrounding soil are crucial for soil temperature recovery and the performance of the buried pipe heat exchanger in GSHP systems. Studies by Retkowski et al. [148] and Gultekin et al. [149] simulated and analyzed the impact of borehole spacing on heat transfer efficiency and soil temperature changes. The results indicated a more significant temperature drop near the borehole, with a maximum decrease of 12°C after 25 years. However, increasing the distance between buried pipes results in larger land area requirements and higher initial investment, which can be challenging to achieve in densely populated cities.

In summary, the long-term operation of GSHP systems can lead to soil thermal imbalances and decreased system efficiency. Increased borehole spacing has been proposed as a solution to mitigate thermal disturbance and extend system life. However, this approach limits GSHP system application and reduces economic benefits. Proper borehole layout and monitoring are essential to optimize the performance and efficiency of GSHP systems while considering the specific cooling and heating loads of the region.

2.5 Summary

This chapter first classifies heat pumps, including air-source heat pumps, water-source heat pumps, and ground-source heat pumps. It then focuses on ground source heat pump systems and discusses the current status of their application and technical bottlenecks.

First, the current status of ground source heat pump applications and research is discussed, highlighting recent advances in implementation and research in this technology area. The development limitations faced by this technology are also analyzed.

Next, the current state of application and research progress of ground source heat pump systems are described. The technological development process is discussed, including the progress made over time. Meanwhile, the technical advantages of ground source heat pump systems are discussed, and the current technical bottlenecks, factors affecting system performance and efficiency are pointed out. Special attention is also given to the technical bottlenecks of ground source heat pump systems in cold regions of China, recognizing the unique challenges faced in implementing ground source heat pump systems in these regions.

Finally, the operational performance and heat balance of ground source heat pump systems are investigated, focusing on the thermodynamic and energy exchange processes involved in system operation.

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Chapter 3

RESEARCH SUBJECTS AND METHODS

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3.1 Research subjects

3.1.1 Ground source heat pump project overview

The study is based on a demonstration project conducted in Changchun, Jilin Province, which is located in the cold region of northeast China. The project focuses on a Class A public building with a height of 23.9 meters and a total construction area of approximately 25,500 square meters. It falls under Building Class I and Seismic Protection Class VII.

The building's primary structure is a frame structure, while the walls are constructed using fly ash autoclaved aerated concrete blocks. The design of this building adheres to the Energy Conservation Design Standard for Public Buildings DB22/436-2007. The local standard in Jilin Province requires a 50% energy-saving target, which translates to around 10-20% energy savings. The public building serves various functions such as lecture halls, teachers' offices, laboratories, multimedia classrooms, meeting rooms, and restrooms. It consists of six floors, with the first and second floors being 3.9 meters high and the third to sixth floors being 3.3 meters high.

The energy-saving design of the building strictly follows the 65% energy-saving standard for public buildings. It is classified as a Class A building, with a body form factor of 0.22. The walls are constructed using 460mm thick fly ash autoclaved aerated concrete blocks, and the exterior walls are covered with 20mm thick dry powder insulation mortar. The inner walls are made of 200mm thick fly ash autoclaved aerated concrete blocks.

The building features plastic steel hollow glass windows with a window-wall ratio of 34% for the exterior windows. The roof is constructed with concrete insulation, and the building is oriented at 14°NW. The appearance of the building can be seen in Fig3-1, while the heat transfer coefficients of the building envelope windows, walls, roofs, and floor slabs, as well as the relevant parameters of the exterior windows, are provided in Table 3-1 and Table 3-2.

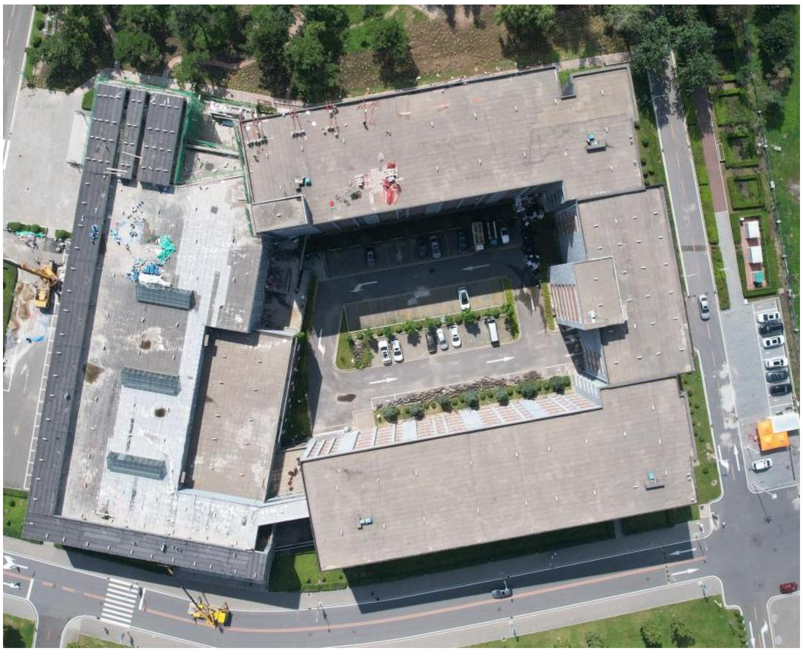

Fig 3-1 Satellite view of the building

Table 3-1 Heat transfer coefficient of the building envelope

Heat transfer coefficient of the wall （W/m² ·K）	Heat transfer coefficient of exterior windows （W/m² ·K）	Heat transfer coefficient of internal wall （W/m² ·K）	Heat transfer coefficient of roof （W/m² ·K）	Heat transfer coefficient of floor slab （W/m² ·K）
0.38	2.20	0.62	0.34	3.06

Table 3-2 Exterior windows related parameters

Orientation	Actual window wall Area ratio	Actual heat transfer coefficient	Shading factor	Openable area	Visible light Transmittance ratio
East	0.067	1.9	0.48	31%	0.4
South	0.245	1.9	0.48	38%	0.4
West	0.064	1.9	0.48	32%	0.4
North	0.39	1.9	0.48	34%	0.4

The ground source heat pump system consists of two main components: the ground source side with its circulation pump, and the air conditioning side with its circulation pump. The system operates differently in winter and summer[1].

Winter Working Process:

Ground source side: In winter, a mixture of water and antifreeze circulates through the underground heat exchanger, extracting heat from the soil. The heated mixture then returns to the underground heat exchanger, completing the energy collection process.

Heat pump unit: The liquid substance in the evaporator absorbs heat from the ground source side, evaporates into a gas state, and then passes through the compressor for compression. It enters the condenser where it releases heat, condenses back into a liquid substance, and returns to the evaporator after decompression by the expansion valve, completing the energy lifting process.

User side: The water in the indoor heating equipment absorbs heat from the condenser gas, heats up, and releases heat into the indoor space. The water then returns to the condenser, completing the energy release process. This cycle continues to extract heat from the ground and provide heating.

Summer Working Process:

Ground source side: In summer, the ground source side acts as a heat dissipation source. Cold water from the indoor side circulates through the underground heat exchanger, transferring heat to the ground.

Heat pump unit: The liquid substance in the evaporator absorbs heat from the cold water on the ground source side, evaporates into a gas state, and then passes through the compressor for compression. It enters the condenser where it releases heat and cools down, condensing back into a liquid substance. After decompression by the expansion valve, it returns to the evaporator, completing the energy lifting process.

Indoor side (user side): Cold water from the ground source side circulates through the indoor cooling equipment, absorbing heat from the indoor space. The water then carries the heat back to the ground for dissipation. This process is repeated continuously to achieve indoor cooling and heat dissipation.

In summary, the ground source heat pump system utilizes the ground as a heat source in winter and a heat sink in summer. It transfers heat between the ground and the indoor space through the circulation of a working fluid and the operation of the heat pump unit, providing efficient heating and cooling throughout the year. The system flow is shown in Fig 3-2. The detailed layout of the plant room is shown in Fig 3-3.

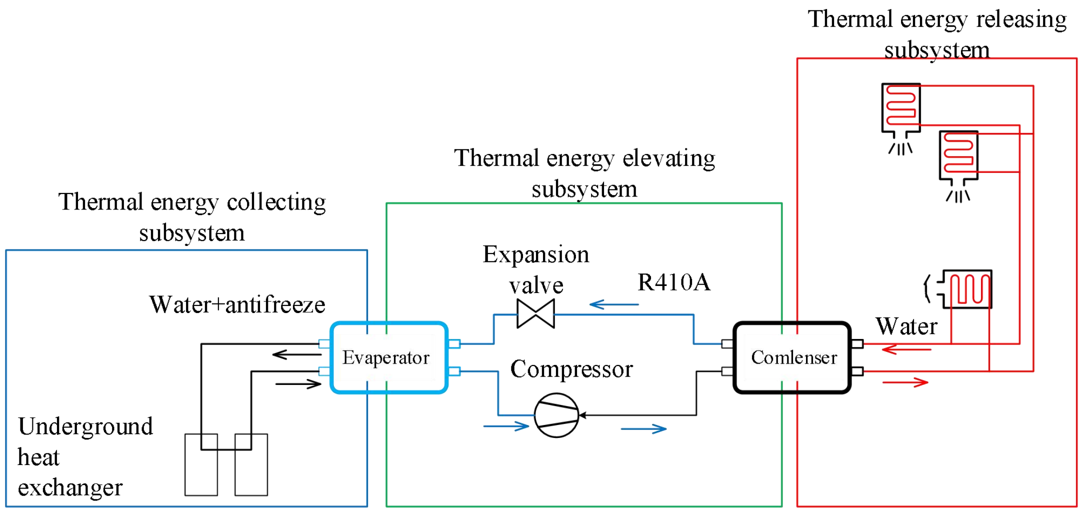

Fig 3-2 System process

Fig 3-3 The detailed layout of the plant room

According to the load of the building, two ground source heat pump CUWD80A5Y-HC units produced by Daikin Air Conditioning were selected for the demonstration project, with a heating capacity of of 186.6kW and a cooling capacity of 211.8kW, with a heating case input power of

50.3kw and a water flow rate of 36.14w/h^3; a cooling case input power of 39.4kw and a water flow rate of 36.5w/h^3, Evaporator flow rate 30.6m^3 /h, condenser flow rate 36 m^3 /h, circulation water pump 6 sets， and the buried pipe is made of polyethylene pipe with an inner diameter of 25mm and an outer diameter of 32mm .The layout of the machine room is shown in Fig 3-4. The main equipment performance parameters are shown in Table 3-3.

Fig 3-4 The layout of the machine room

Table 3-3 Equipment parameters of GSHP

Device	Model	Quantity	Heating congdition /Cooling condition (kW)	Pump head (m)	Flow (m3/h)
GSHP	AQSW0612	2	184.1/216.6	-	-
Circulating pump	QPG80-160	3	-	28	46.7
Circulating pump	QPG80-160	3	-	24	43.3

3.1.2 Area compensation technology

In cold regions, the demand for heating during winter is significantly higher compared to the cooling demand in summer. This can lead to a thermal imbalance in the soil over time. To prevent such imbalances and optimize the design, annual energy consumption simulations were conducted using DeST-c software. These simulations calculated parameters including annual energy consumption, peak load, and hour-by-hour load values.

Fig 3-5 illustrates the results of the simulations. The calculations revealed that the annual accumulated heat required for winter was 1.350×107 kW h, while the accumulated cooling required for summer was 0.714×107 kW h. This indicates a ratio of 1.891:1 between the heat requirements in winter and cooling requirements in summer.

By considering these energy consumption ratios and load values during the design phase, it is possible to achieve a more balanced and efficient ground source heat pump system that can meet the heating and cooling demands of cold regions while minimizing thermal imbalances in the soil.

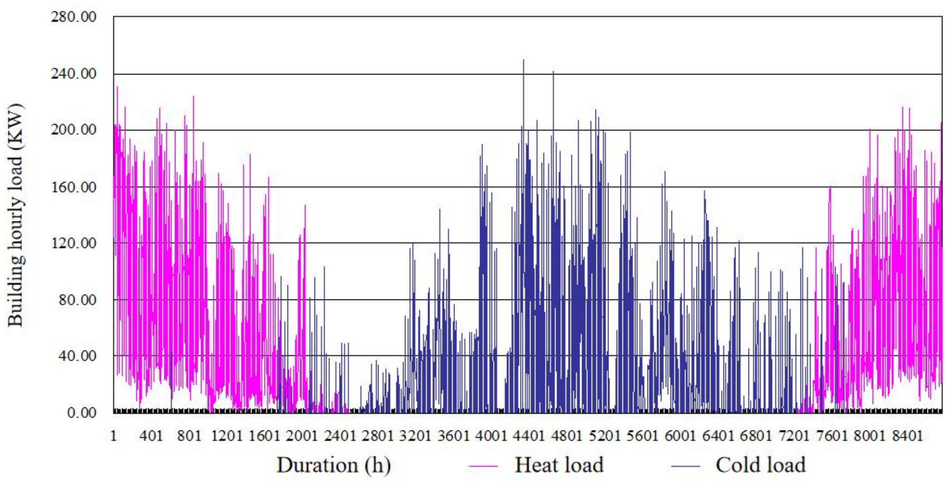

Fig 3-5 Building annual heat and cold load

The demonstration project implements the area heat compensation technology for regional cooling and heating to achieve a balance in heat supply between winter and summer. Fig 3-6 illustrates this approach, where the cooling area consists of areas A and B, covering a total area of 14,999.7 m^2. In contrast, the other areas do not require cooling. The heating area corresponds to area B, with a size of 8,386.2 m^2. For the remaining areas, the urban thermal network takes responsibility for meeting their heating and cooling needs, as depicted in Fig 3-7.

The ratio between the cooling area and the heating area is 1.789:1, indicating that the cooling area is larger than the heating area. By strategically controlling the distribution of heating and cooling areas, the project aims to achieve a fundamental balance between the amount of heating and cooling. This approach allows for efficient utilization of the ground source heat pump system and helps prevent thermal imbalances.

By adopting the area-based approach, the demonstration project optimizes the allocation of heating and cooling loads, ensuring a more balanced and effective operation of the ground source heat pump system throughout the winter and summer seasons.

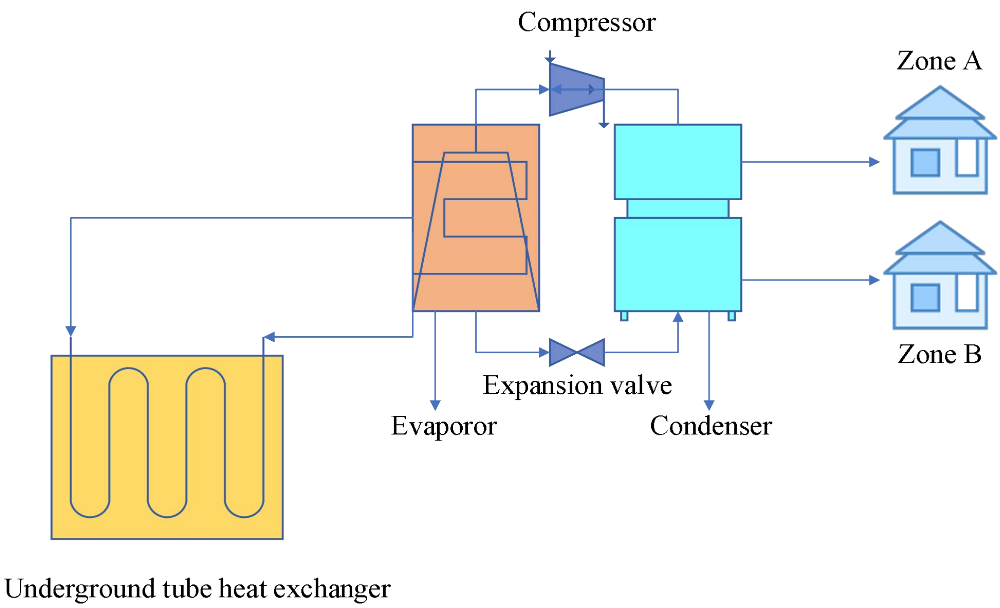

Fig 3-6 GSHPs summer cooling zoning control principle

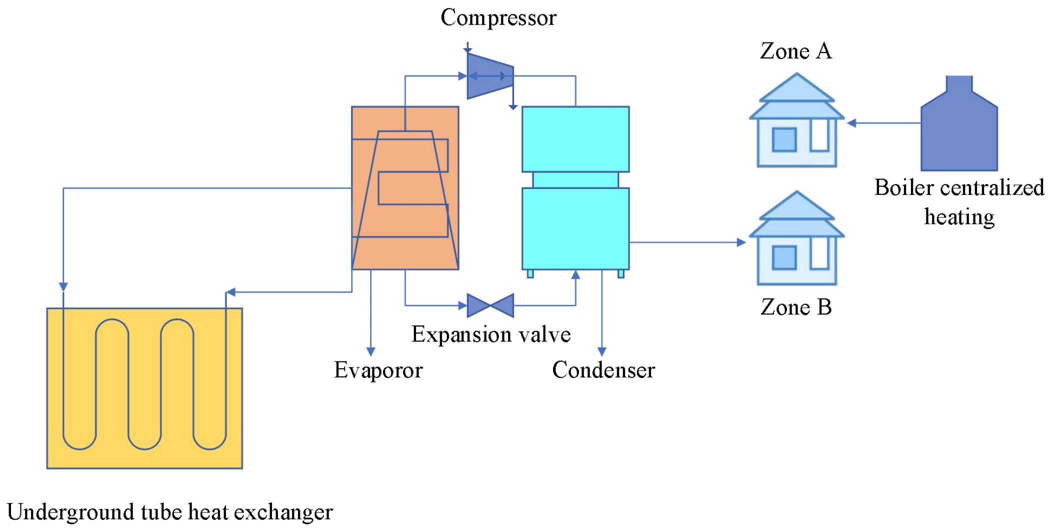

Fig 3-7 GSHPs winter heating zoning control principle

In the project, based on the calculation of the winter heat load and soil heat exchange value, it is determined that 104 heat exchange holes are required. To account for a 15% drilling safety allowance, a total of 120 heat exchange holes are set. These heat exchange holes are designed to accommodate double U-shaped buried pipes, with each hole having a depth of 100 meters and a diameter of 180mm. The layout form and spacing of the heat exchange holes play a crucial role in optimizing the heat exchange efficiency of the buried pipes in the ground source heat pump system[2]. According to the GSHP Engineering Technical Specifications of China's national standard[3], it is recommended to set the heat exchange hole spacing between 3m and 6m. In this project, three different heat exchange hole spacing options of 4m, 5m, and 6m are employed. The arrangement of the heat exchange holes can be observed in Figure 3-8, which showcases the specific layout of the heat exchange holes within the project site.

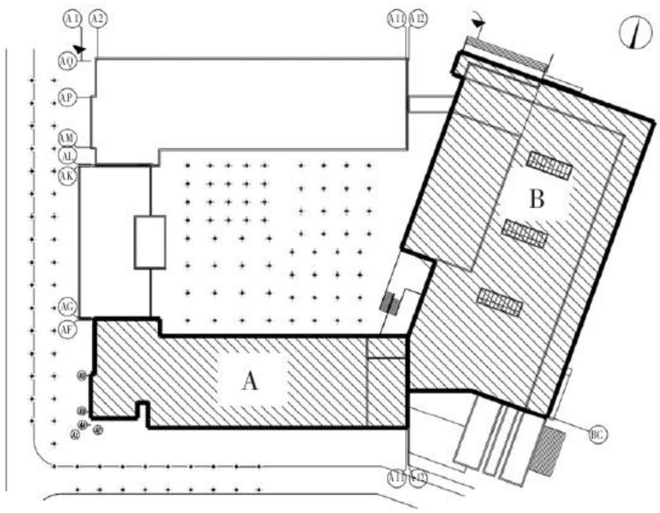

Fig 3-8 Heating＆cooling zoning and underground heat transfer well layout

3.2 Data source

3.2.1 Natural conditions of the project site

The project site is situated in Nanguan District, Changchun City, Jilin Province, Northeast China. Changchun City, located at latitude 43°N and longitude 125°E, is characterized by being in the interior of the Northeast Plain, one of the three major plains in China[4]. The region experiences a typical continental monsoon climate, transitioning from a humid zone to a subarid zone. The climatic characteristics of Changchun City are marked by significant temperature variations throughout the four seasons. Winters are dominated by severe cold, accompanied by prevailing northwest winds. Summers, on the other hand, exhibit moderate high temperatures and humidity. The city receives approximately 2688 hours of sunshine annually.

The average annual temperature in Changchun City is 4.9 ℃, with July being the hottest month. During July, the maximum temperature reaches 38 ℃, while the minimum temperature drops to -36.5 ℃. The average winter temperature falls below -11 ℃, while the average temperature during the hottest month, July, is 23 ℃. Precipitation in the region is primarily concentrated in summer, accounting for more than 60% of the annual precipitation. On average, Changchun City receives 522 to 615 mm of rainfall annually[5].

Table 3-4 reflects the outdoor design parameters required for heating and air conditioning in the Changchun area, providing specific data on the climatic conditions that need to be considered for the project[6].

Table 3-4 Outdoor meteorological parameters of Changchun City

Heating days Z(d)	Heating degree-days (℃.d)	Mean temperature (℃)	Outdoor dry bulb temperature for heating(℃)	Outdoor relative humidity for heating(%)	Minimum temperature (℃)
168	4471	4.8	-23	69	-39.8

METEONORM software, developed by the Swiss company MeteoTest, is used to calculate the meteorological parameters of the project site[7]. METEONORM software contains a comprehensive global climate database, the principle of which is based on remote sensing technology and meteorological databases using mathematical means such as interpolation and monthly average value models, radiation resolution, hourly value generators, etc. to process meteorological data in the horizontal Radiation and temperature based interpolation using weather data in terms of elevation, topography, area, etc. dependent on space. The software is mainly used in the solar engineering and photovoltaic industries, but is also widely used in building energy efficiency, environmental research, agriculture, forestry and other fields to provide scientific meteorological data for energy consumption simulation.

Fig 3-9 Software interface of METEONORM

The coordinates of Changchun city are 43.90° N, 125.21° E and 238m above sea level. Using 30 years of temperature data and 20 years of solar radiation data of Changchun area, we generate 8760 hours of hour-by-hour weather data in tmy2 format by stochastic algorithm. It includes meteorological parameters such as the hour-by-hour outdoor dry bulb temperature of Changchun, the monthly average sunshine duration of Changchun, the monthly outdoor dry bulb temperature distribution statistics of Changchun, the annual solar radiation intensity of Changchun, the precipitation curve of Changchun, the moisture content, and the monthly average radiation intensity of Changchun.

Fig 3-10 and Fig 3-11 present the hour-by-hour dry bulb temperature data of the project site throughout the year, providing a comprehensive understanding of the temperature variations. Fig 3-12 displays the variation curve of local solar radiation intensity, indicating the changes in solar radiation received at the project site.

Fig 3-13 showcases the monthly average histogram of radiation intensity in Changchun. The chrysanthemum red color represents the level of diffuse radiation horizontally, while the yellow color represents the level of direct radiation horizontally. It can be observed that the month of May experiences the highest level of direct radiation exposure, while August exhibits the highest level of diffuse radiation.

Fig 3-14 presents the monthly average sunshine duration data in Changchun. The red color represents the sunshine duration, while the yellow color represents the astronomical sunshine duration. This figure provides insights into the amount of time the sun is visible throughout the year.

Fig 3-15 illustrates the annual precipitation in Changchun. The red line, based on the left coordinate, represents the average number of days of precipitation per month, while the blue area, based on the right coordinate, represents the precipitation amount. This figure helps to understand the distribution and quantity of precipitation throughout the year in the region.

Fig 3-10 Annual outdoor dry bulb temperature hours in Changchun

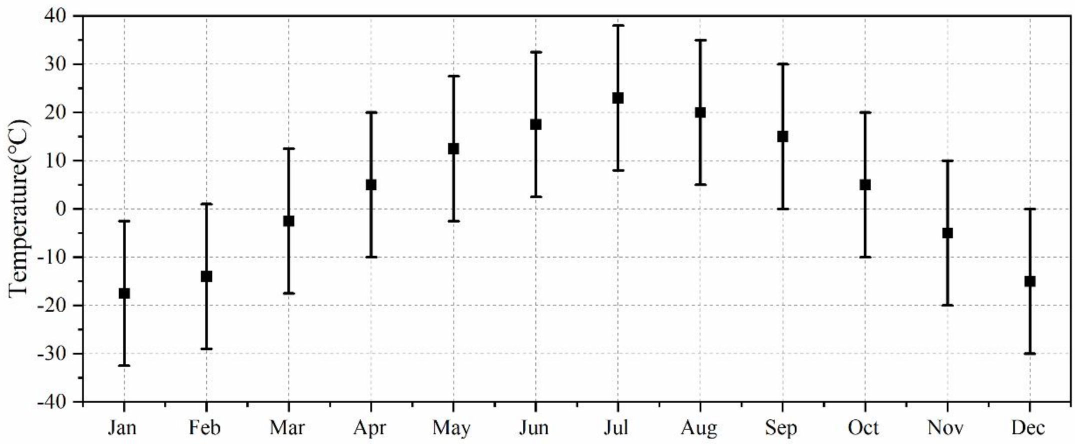

Fig 3-11 Statistics of outdoor dry bulb temperature distribution in Changchun by month

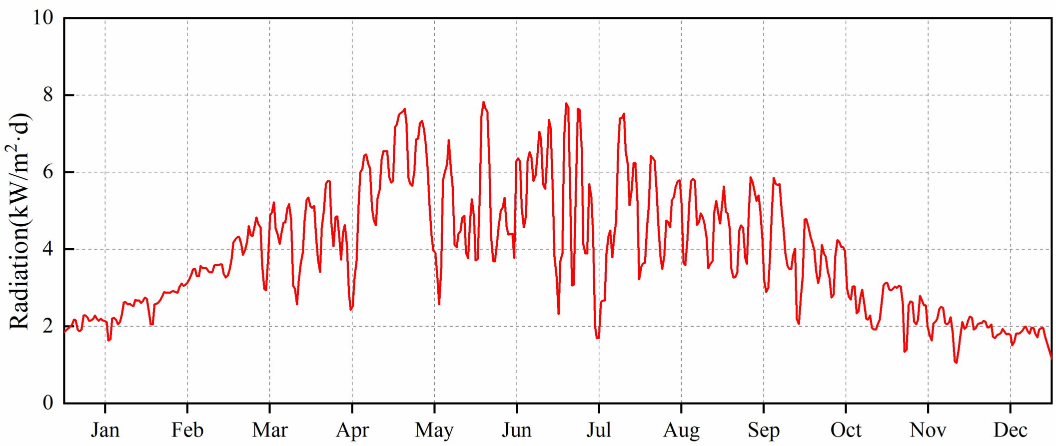

Fig 3-12 Annual solar radiation intensity in Changchun

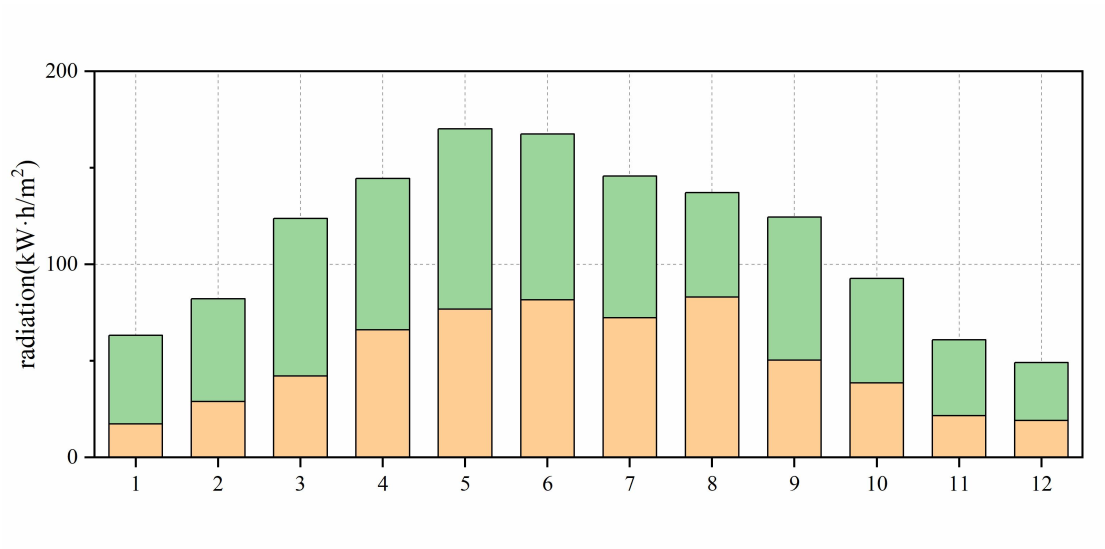

Fig 3-13Average radiation intensity in Changchun

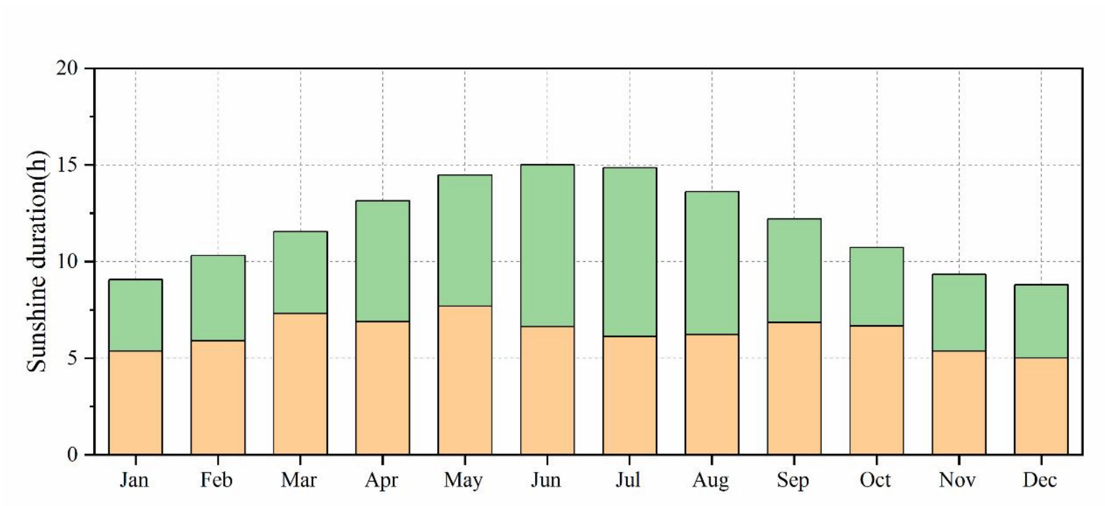

Fig 3-14 Average sunshine hours in Changchun

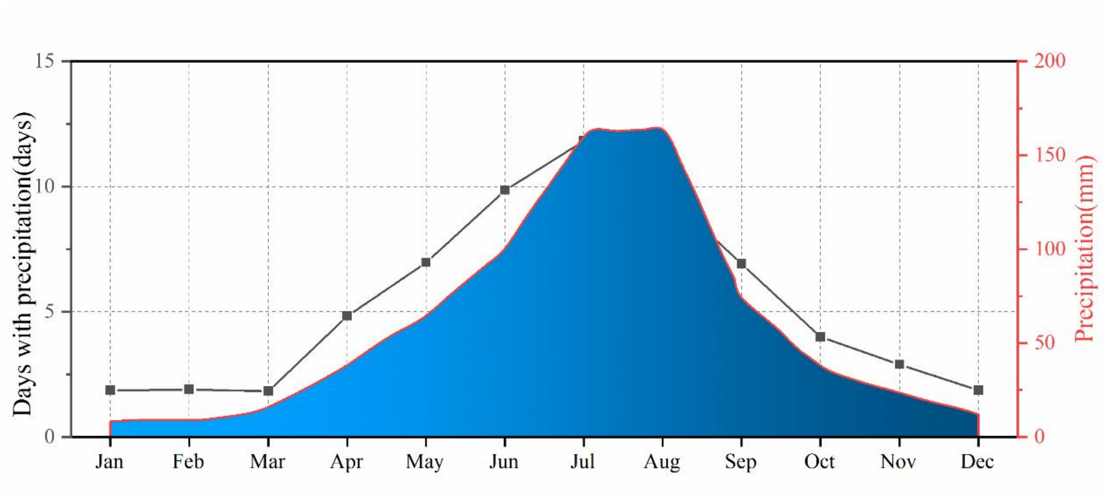

Fig 3-15 Precipitation curve in Changchun

3.2.2 Stratigraphic thermal property parameters

The soil physical parameters of the area where the ground source heat pump system is located include the average temperature of the geotechnical thermostat layer, the average heat transfer coefficient, the heat exchange per linear meter, etc. The design depth of the test hole at the site is 100m, the actual depth is 92m, the hole diameter is 180mm, and the 32mm diameter U-type HDPE buried pipe heat exchanger is buried in the hole, and the backfill material is raw slurry backfill. After surveying the stratigraphy around the project conditions are shown in Table 3-5 below:

Table 3-5 Classification of geological conditions

Depth (m)	Geological category	Main geological components
0~8	Fourth Department	Clay, pulverized clay
8~23	Fourth Department	Coarse sand, medium coarse sand
23~49	Cretaceous	Moderately weathered and weakly weathered mudstone and sand conglomerate
49~92	Cretaceous	Slightly weathered mudstone, sand conglomerate

In ground source heat pumps, the heat transfer capacity of the buried tube heat exchanger system depends mainly on the thermophysical property parameters of the stratum around the buried tube, and these thermophysical property parameters need to be tested out experimentally. The teaching library uses an in-situ tester of the thermal-physical properties of the ground for both heat storage and heat extraction conditions, measures the initial average temperature of the ground, and uses the data obtained from the test and the calculation software to calculate and analyze the data such as the average heat transfer coefficient of the ground between the heat exchanger and the surrounding strata, and the heat exchange rate per linear meter of the heat exchange well. These data provide accurate design parameters for the design calculation of the buried tube heat exchanger; they also provide accurate data for the simulation calculation of the operation condition of the soil source heat pump system[8].

Data such as flow rate and temperature of circulating fluids at different locations in the pipeline are measured using flow and temperature sensors and transmitted to the acquisition and control system of the tester, and then the heat transfer model is used to calculate the average thermal conductivity of the formation and the thermal resistance of the borehole, etc.[9]. The in situ tester for the thermal-physical properties of the formation is shown in Fig 3-16. The testing process includes:

(1) Test of the average initial temperature of the stratum around the heat exchanger hole . Without turning on the heat pump unit, i.e. without delivering or extracting heat to the borehole, the circulation pump is turned on alone and the average temperature of the circulating water of the buried pipe heat exchanger is measured, and when this temperature remains stable, it is approximated as the average undisturbed temperature of the rock and soil around the borehole.

(2) Stratigraphic thermal property test. The heat pump unit and heater were turned on and tested in two operating modes, heat extraction and heat storage, respectively. During the test, heat

is extracted (or input) from the ground with constant power, and data such as circulating water flow, temperature of each measurement point, current and voltage of the main electrical equipment are automatically recorded by the data acquisition and monitoring system in real time, and this test process generally lasts for at least 48 hours. After the test, the relevant heat transfer model is used to calculate the average heat transfer coefficient of the ground and the heat transfer rate per linear meter of the buried pipe heat exchange wells, etc.

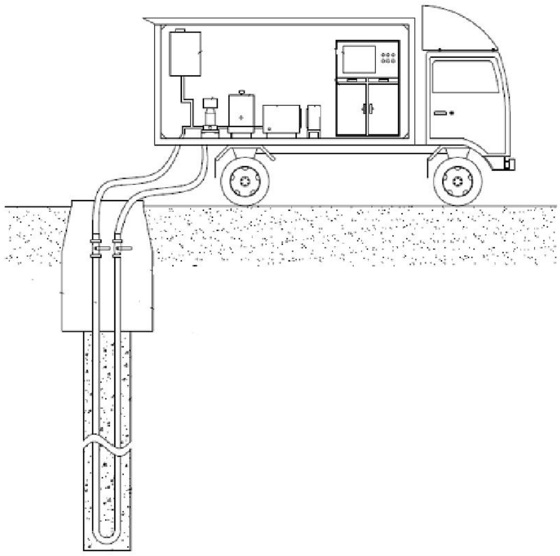

Fig 3-16 Schematic diagram of stratigraphic thermal property tester test principle[10]

The heat pump system operates in winter by extracting heat from the ground through a buried pipe heat exchanger. The testing of the heating operating conditions that was conducted to simulate this operating condition. The flow rate was 1.08 m3/h and the test time was 3400 minutes (about 57 hours). The variation curves of inlet and outlet water temperature, flow rate, and heat input to the borehole with operating time are shown in Fig 3-17 and 3-18.

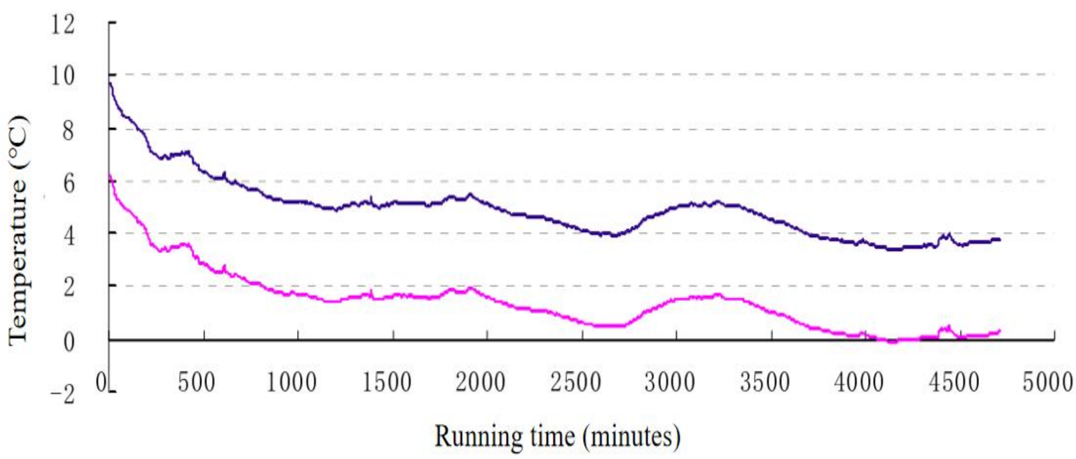

Fig 3-17 Inlet and outlet water temperatures under heating conditions

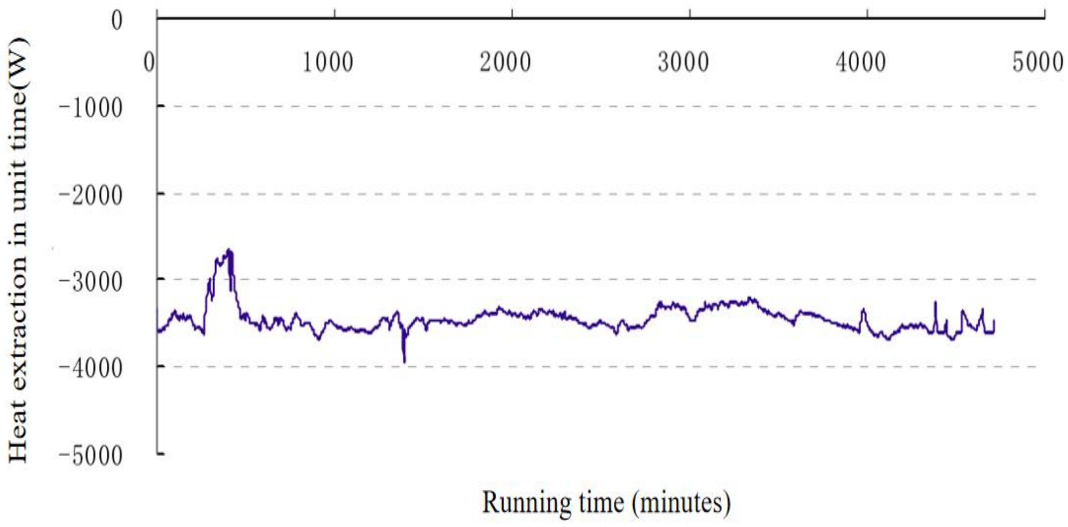

Fig 3-18 Heat extraction by borehole per unit time

The calculation of the thermal conductivity of subsurface soils needs to be combined with the parameter estimation method using a line heat source model to calculate the thermal conductivity of the soil using measured temperature, flow rate and other data[11].

(1) Line source model

The common borehole diameter in ground source heat pump projects is 100-200mm and the depth of the borehole is 100-150m. Since the depth of the borehole is much greater than its diameter, the axial guide heat of the soil and its backfill material around the borehole can be neglected and only the heat conduction within the cross section is calculated. The heat exchanger can be buried vertically in the ground is simplified as a uniform line heat source, the corresponding conditions can also be simplified as follows: the subsurface soil is approximated as infinite and has the same initial temperature of the heat transfer medium; the soil around the borehole does not change with the change in temperature, its thermal properties uniform; ignore the diameter of the borehole, the borehole is approximated as a single line heat source on the center of the borehole, and do not count the heat transfer along the depth of the borehole direction; buried pipe and The heat flow density between the buried pipe and the surrounding soil is kept constant[12]. Based on the above assumptions, the final heat transfer equation for heat transfer from the buried tube heat exchanger to its surrounding rock and soil can be transformed into an equation between the average temperature of the circulating medium inside the tube and the initial temperature of the surrounding rock and soil as follows:

$$T_f = T_{ff} + q_1 \bullet \left[R_0 + \frac{1}{4\pi k_s} \bullet Ei\left(\frac{d_b^2 \quad \rho_s C_s}{16 k_s \tau} \right) \right] \tag{3-1}$$

Where， d_b is diameter of the borehole, m; $\rho_s C_S$ is volumetric specific heat capacity of the rock and soil, J/(m^3-K);ks - heat transfer coefficient of the surrounding rock and soil, W/(m-K); τ is time, s; q_l - intensity of heat flow from a linear heat source per unit length, W/m; R_0 is total thermal resistance per unit length of the borehole, K/(W-m); T_f - the average temperature of the circulating medium in the buried pipe, ℃; T_{ff} - the initial undisturbed temperature of the surrounding rock and soil,℃.

The geotechnical thermal conductivity is calculated on the basis of the online source model combined with the parameter estimation method. That is, the difference between the calculated average temperature and the measured average temperature of circulating water is reduced by adjusting the geotechnical thermal conductivity, etc., and the requested parameter value is obtained when the sum of squares of the differences is minimized. The calculation formula is:

$$f = \sum_{i=1}^{n} \left(T_{mea,i} - T_{cal,i}\right)^2 \quad (3\text{-}2)$$

The flow of the parameter estimation method to calculate the geotechnical thermal property parameters is shown in Fig 3-19.

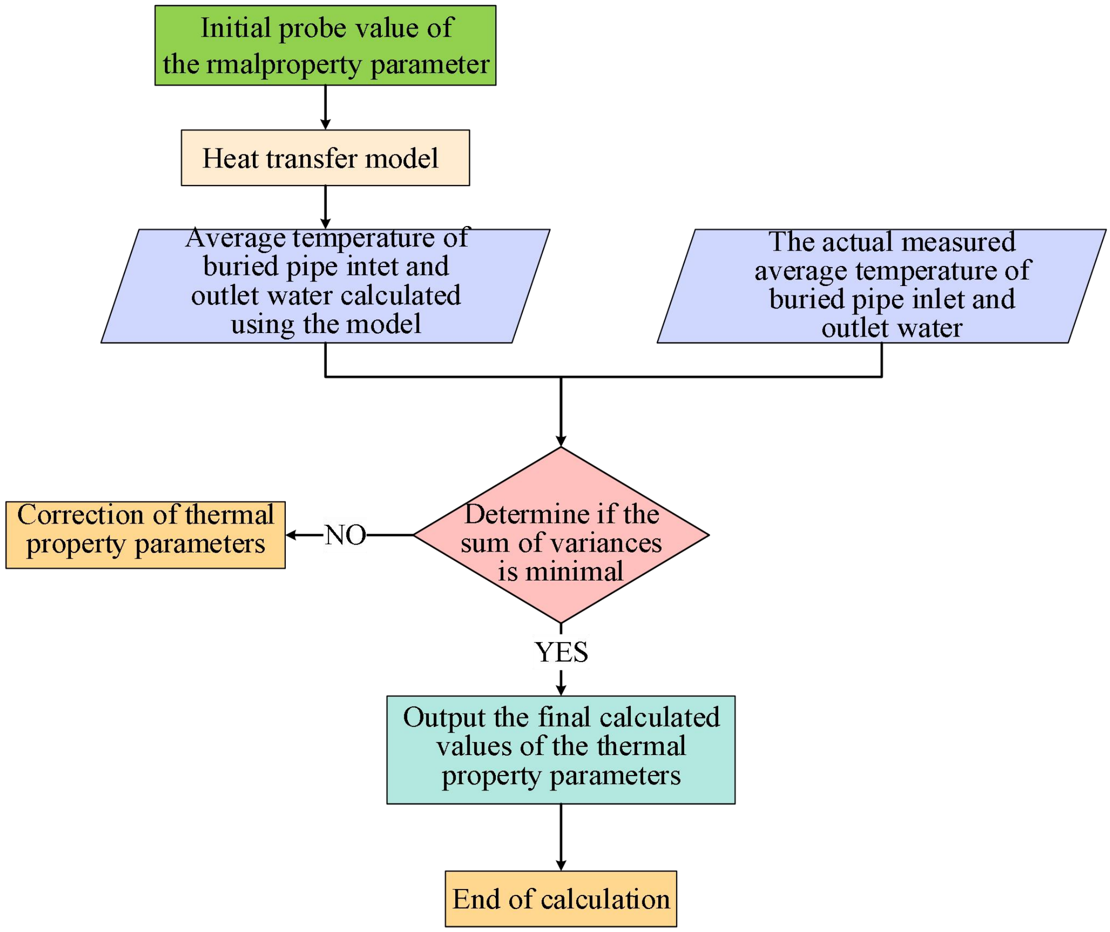

Fig 3-19 Calculation of stratigraphic thermal property parameters flow

(2) Fitting calculation of thermal conductivity

The line source model combined with the parameter estimation method was used to prepare a calculation program with MATLAB software for the fitting calculation. The fitted curves under heating conditions are shown in Figure 3-20.

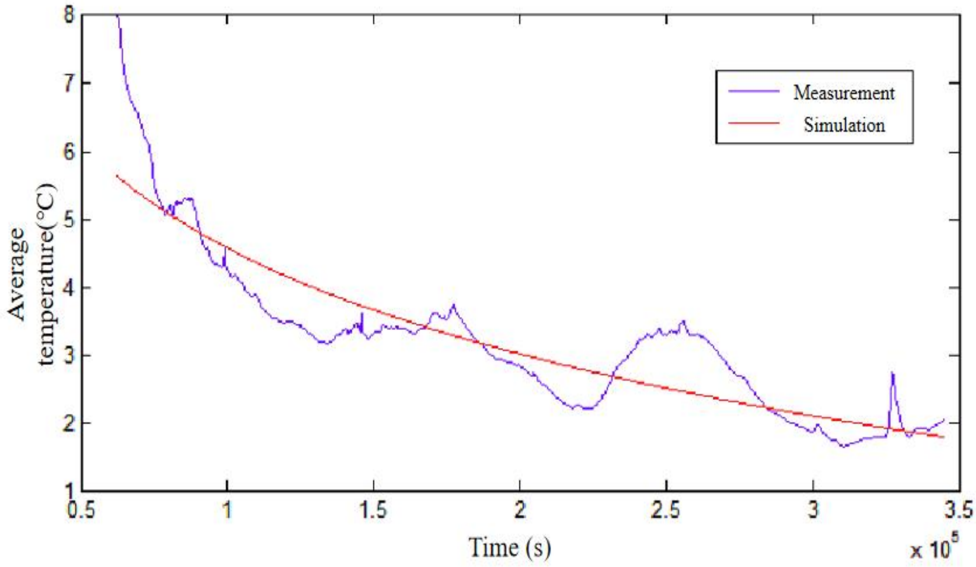

Fig 3-20 The fitting curve on regenerative condition

The soil thermal physical property parameters around the heat exchange hole measured through the preliminary exploration of the project and soil thermal response test are shown in Table 2-12.

Table 3-6 Soil thermal property parameters

Original soil temperature (°C)	Soil heat transfer coefficient W/(m·°C)	Soil density (kg/m³)	Specific heat capacity of soil J/(kg·°C)	Heat transfer (w/m)
8.31	2.573	2200	950	25

3.2.3 Monitoring system for GSHPs

The increasing number of ground source heat pump projects in China has revealed a disparity in the design, construction, and operation management levels of these systems. Some ground source heat pump systems exhibit significant deviations from their design expectations, leading to high operational energy consumption and even system paralysis[13]. This situation poses a challenge to the widespread adoption of ground source heat pump technology.

In 2009, the Ministry of Finance and the Ministry of Construction introduced The Implementation Plan for the Demonstration of Renewable Energy Building Application in Cities[14] and the Technical Guidelines for the Data Monitoring System of Renewable Energy Building Application Demonstration Projects[15]. These guidelines aimed to conduct pilot projects for renewable energy building applications across the country and emphasized the establishment of real-time monitoring devices for ground-source heat pump data.

Currently, the monitoring mechanism for ground source heat pump system operation is not well-established. Many projects lack the necessary conditions for monitoring, and the monitoring, analysis, diagnosis, and evaluation of these systems often rely on manual data reading by property management personnel. This approach is primitive, time-consuming, labor-intensive, and fails to manage and maintain the operation of ground source heat pump systems in a timely manner.

Therefore, there is an urgent practical need and significant practical significance for scientific and reasonable real-time monitoring and evaluation of ground source heat pump systems. Implementing such monitoring and evaluation practices can ensure the effectiveness of ground source heat pump systems in practical applications. Additionally, it plays a crucial role in protecting hydrology, ecology, and geology, as well as regulating the development of the industry.

The real-time monitoring system consists of two parts, one is the data monitoring center, i.e., the data acquisition device as shown in Fig 3-21; the other part is the data acquisition base station, which contains outdoor data acquisition base station and indoor data acquisition The monitoring system is composed as shown in Fig 3-22.

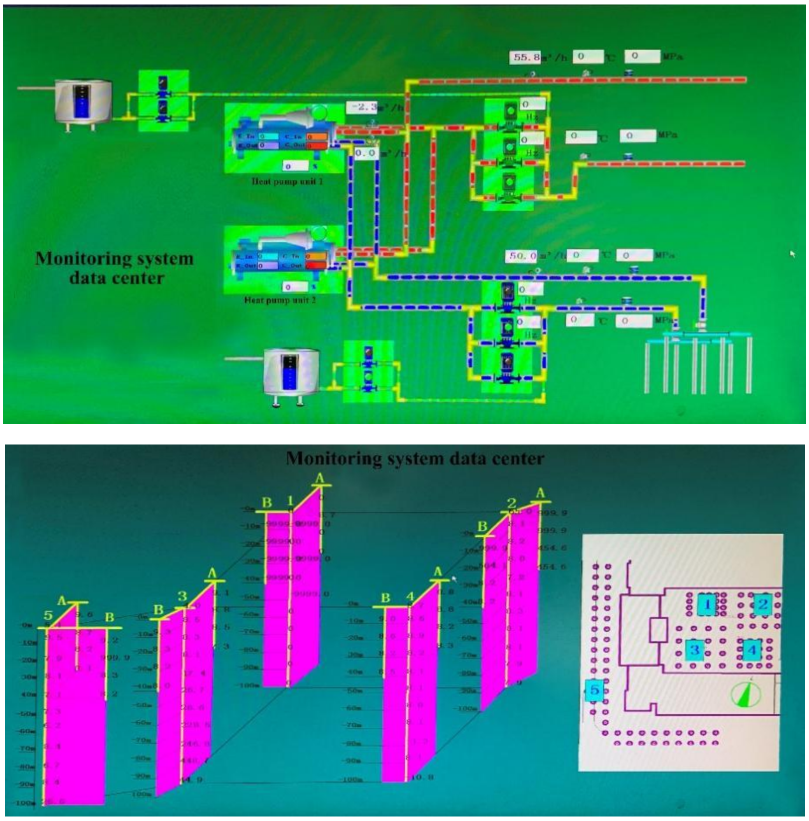

Fig 3-21 Monitoring system data center

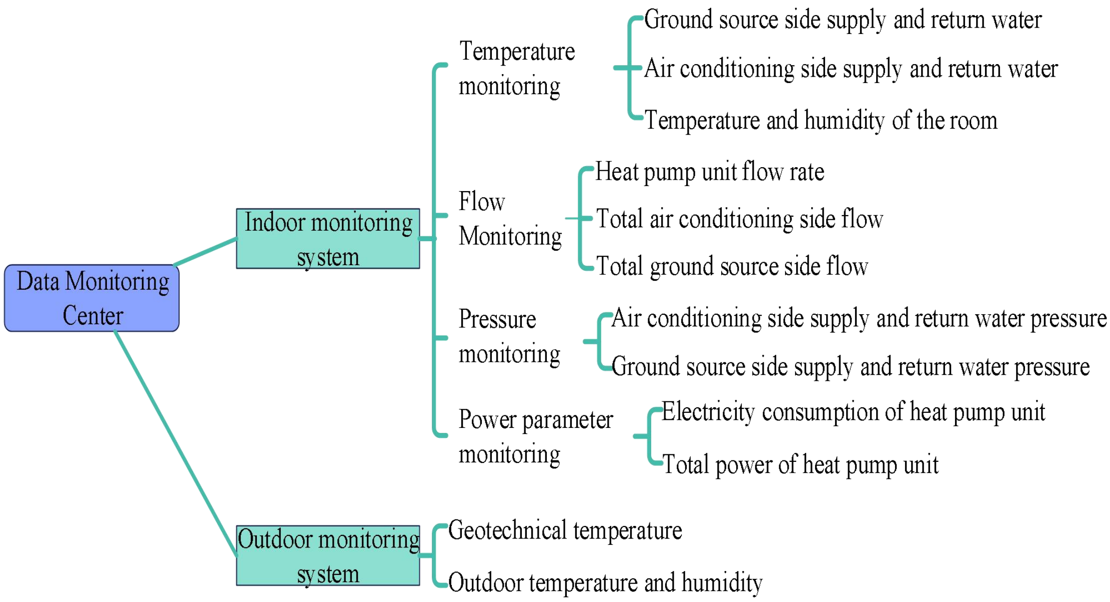

Fig 3-22 Components of the monitoring system

The indoor monitoring system is mainly composed of four parts: temperature monitoring, flow monitoring, pressure monitoring and power parameter monitoring. Among them, temperature and humidity monitoring includes heat pump unit supply and return water, air conditioning side supply and return water, typical room temperature and humidity, flow and pressure monitoring includes heat pump system ground source side and air conditioning side total flow. There are four sets of flow sensors on the ground source side and air conditioning side of the heat pump unit, and the monitoring mainly includes the power, voltage and current of each unit and the total power, voltage and current of the system.

The outdoor monitoring system mainly consists of two parts: outdoor temperature and humidity monitoring and geotechnical temperature monitoring. To avoid direct sunlight, it should be equipped with a special radiation shield and installed in a place with air circulation. During the construction process, the temperature sensor is placed on the PE pipe and put into the heat exchange well, which can realize real-time monitoring of soil temperature changes in the horizontal and vertical directions.

The ground source heat pump monitoring system in this demonstration project encompasses various monitoring functions, including data acquisition, transmission, display, and fault diagnosis.

Data acquisition function: The system automatically collects data at an average interval of five minutes. The main parameters collected include temperature, power, and flow. A data information manager is integrated into the system to support data storage.

Data transmission function: Communication protocol information exchange is used for data transmission. The data information management system acts as the host, while the metering devices listen to request instructions from the data information management system.

Data display function: The ground source heat pump supervisory room is equipped with data information monitoring software. This software processes the collected data and presents it in the form of tables and images, offering intuitive and clear results.

Fault diagnosis function: The system includes a fault diagnosis function. If the metering equipment fails to respond to three consecutive commands, the data management system identifies it as a system fault and displays the fault information on the data display system. This function improves operational efficiency and ensures the stable operation of the unit.

This monitoring system enables the monitoring of key energy efficiency parameters, facilitates the comprehensive energy-saving assessment of the entire system, and provides data support for the efficient operation of the ground source heat pump system.

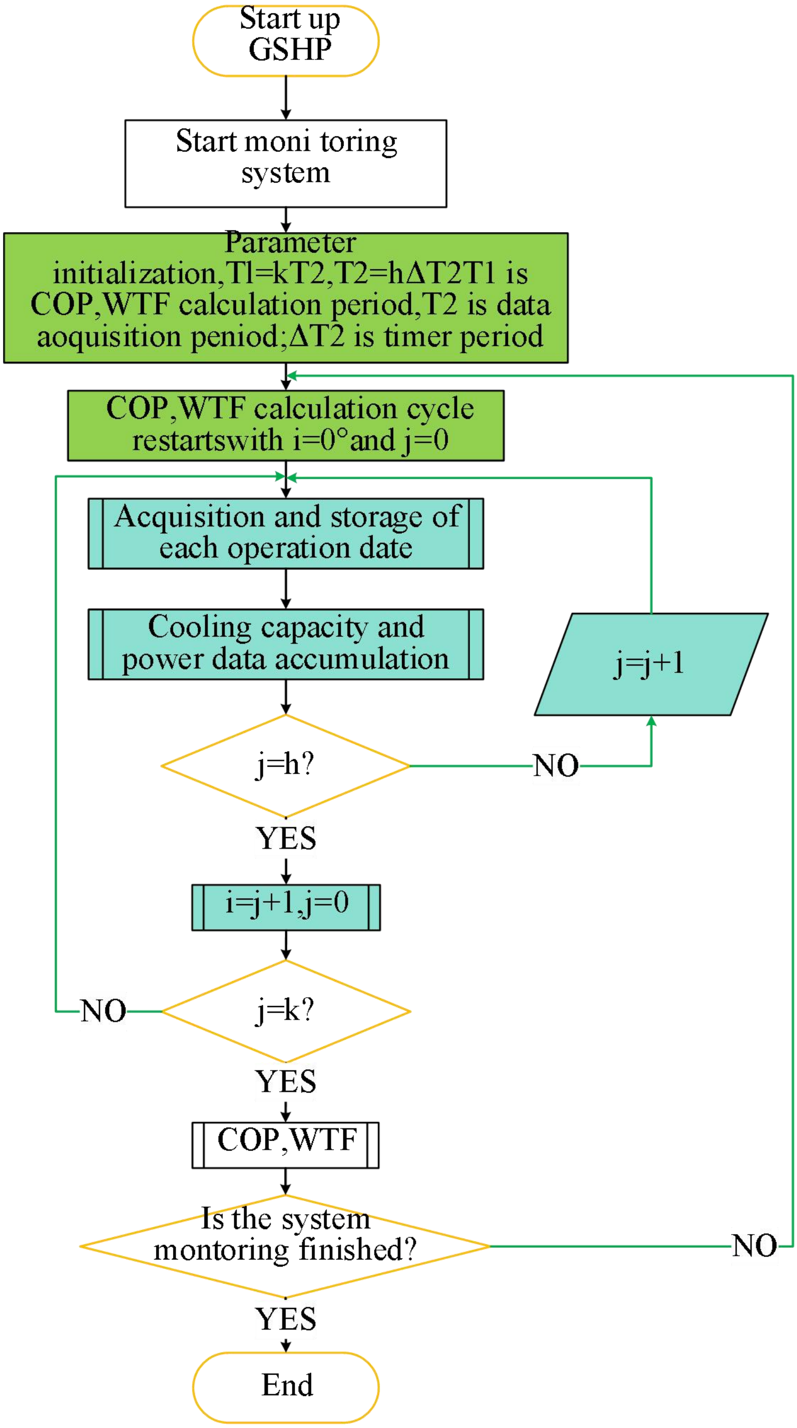

Fig 3-23 Working process of monitoring system

The main working process of the monitoring system is shown in the figure below, after the heat pump unit is started, the monitoring system is started, the calculation period of the energy efficiency value T1 is an integer multiple of the data collection period T2, T1=AT2, the data collection period is an integer multiple of the timing period ΔT, T2, =B ΔT, after the initial value is assigned to the collection period, the intermediate variables i and j are assigned the initial value 0, the main data to be monitored are outdoor The main data to be monitored are outdoor temperature, supply and return water temperature of heat source side, supply and return water temperature of air conditioner side, flow rate of heat source side and air conditioner side, power consumption and unit input power, and the received data are uploaded to the data area.

To monitor the real-time changes in the soil temperature field at different well spacing, four groups of monitoring areas were established within the array layout area. The distribution diagram of these four groups of monitoring wells is presented in Fig 3-24. Each group consists of one main monitoring well and two auxiliary monitoring wells. The detailed layout of the monitoring wells is illustrated in Fig 3-25.

The main monitoring well is 100 meters deep and is equipped with 11 temperature measurement points. The shallowest measurement point is located at -2.5 meters, with the remaining points set at 10-meter intervals. The two auxiliary monitoring wells are 40 meters deep and are positioned on both sides of the main monitoring well at intervals of 1 meter and 2 meters. Within the depth range of -10 meters to -40 meters, temperature measurement points are placed at 10-meter intervals. The arrangement of temperature sensors in the monitoring wells is depicted in Fig 3-26.

The main monitoring well serves as the actual heat exchanger well in the project. During construction, three-wire system PT1000 temperature sensors are fixed on the PE pipe according to the required spacing. The PE pipe, along with the temperature sensors, is then lowered into the drilled heat exchange well. This monitoring system allows for real-time monitoring of soil temperature field changes at different depths and longitudinal directions. It also enables the assessment of soil temperature field variations within the same geotechnical layer, transverse direction, and horizontal direction, as well as the interaction between the heat exchange wells.

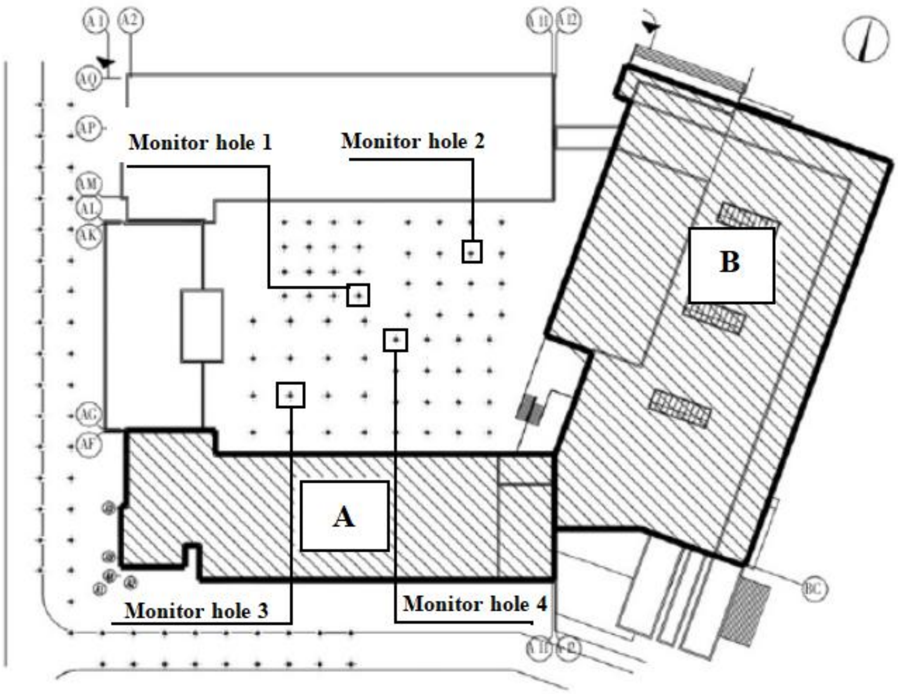

Fig 3-24 Monitoring well layout diagram

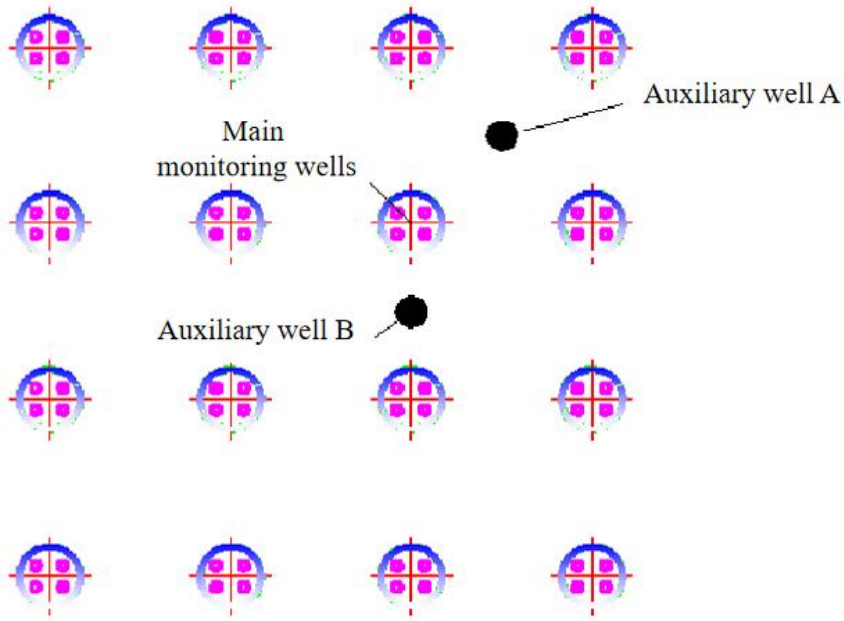

Fig 3-25 Detailed drawing of monitoring well layout

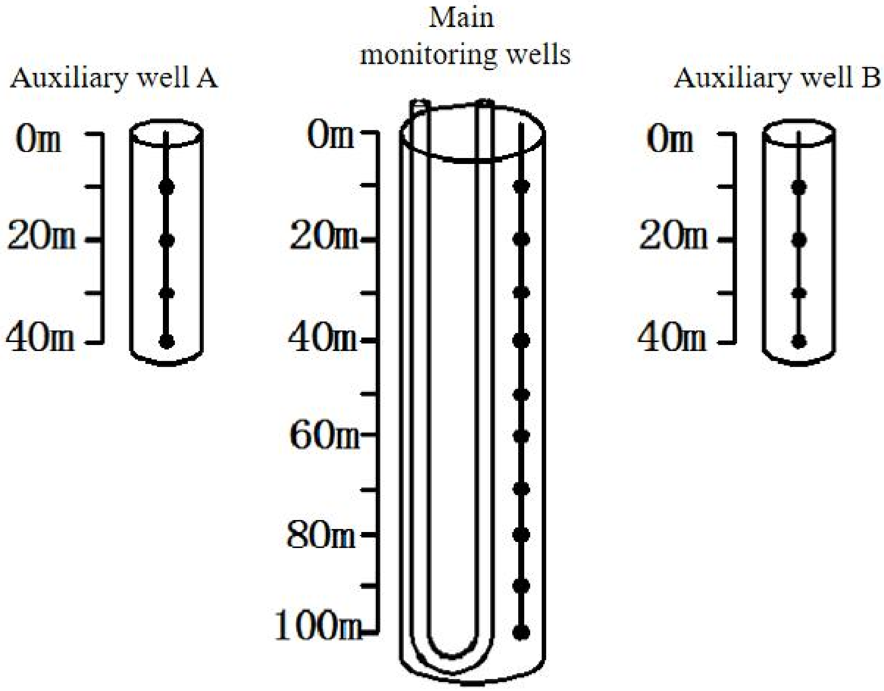

Fig 3-26 Monitoring well temperature sensor arrangement

Outdoor air temperature and humidity collection using TS-TWO5Y-2306 outdoor temperature and humidity sensor, equipped with radiation protection cover, appearance as shown in Fig 3-27, the sensor technical parameters are shown in Table 3-7. outdoor temperature sensor installed in a well-ventilated, air circulation, and avoid direct sunlight.

Fig 3-27 Outdoor temperature and humidity sensor

Table 3-7 Outdoor temperature and humidity sensor technology parameters

Measurement range (℃)	Accuracy (℃)	Resolution (℃)	Long-term stability (℃/year)
-40~+80	≤±0.3	≤±0.1	<0.1

Indoor temperature and humidity monitoring is placed in a typical room in the building, using the model JWSL-6-W1WD wall-mounted RS-485 network type temperature and humidity sensor with LCD display, standard with 1m signal cable, extended distance need to connect 4*1 shielded cable. The appearance of the equipment is shown in Fig 3-28.

Fig 3-28 Indoor temperature and humidity sensor

The temperature monitoring points include the total supply and return water temperature on the air conditioning side and ground source side of the heat pump system, with a total of 4 sets of temperature sensors. The temperature sensor adopts the temperature sensor of JWB series, and the output signal is 4~20mA or 0~10V analog output. The temperature sensor is threaded installation, see Fig 3-29 for appearance, and see Table 3-8 for technical parameters.

Fig 3-29 Water supply and water temperature sensor

Table 3-8 Water supply and water temperature sensor technology parameters

Measurement range (℃)	Accuracy (℃)	Output (m A)	Resolution (℃)
0~100	≤±0.2	4~20 DC	≤±0.1

Flow monitoring points include the air conditioning side and ground source side flow of one of the heat pump units, the air conditioning side and ground source side total flow of the heat pump system, a total of four groups of flow sensors. Flow sensor using TDS series ultrasonic flowmeter, RS485 communication interface ModubusRTU standard communication protocol, power AC220V, with standard M1 probe, with field display. Ultrasonic flowmeter appearance see Fig 2-31, technical parameters see Table 3-9.

Fig 3-30 Flow sensor

Table 3-9 Flow sensor technology parameters

Accuracy (%)	Resolution (m^3/h)	Working ambient temperature(℃)	Relative humidity of working environment (%)
≤1	≤0.1	0~50	20~80

Pressure monitoring points include the ground source side of the heat pump system and the air conditioning side of the total supply and return water pressure, a total of four pressure sensors, pressure sensors using the JYB series of pressure transmitters, output 4 ~ 24 mA, using threaded installation, the appearance of Fig 3-31, technical parameters are shown in Table 3-10.

Fig 3-31 Pressure pickup

Table 3-10 Pressure sensor technology parameters

Range (KGf)	Accuracy (level)	Output (m A)	Supply voltage (V)
0~10	0.2	4~20 DC	DC 12~32

Indoor data acquisition base station power monitoring points include each heat pump unit power parameters (current, voltage, power) and total system power parameters (current, voltage, power). (current, voltage, power) and the total power parameters of the system (current, voltage, power), a total of three groups of power sensors. The power sensor adopts S7-330 series multi-functional meter, which adopts RS 485 communication interface, ModubusRTU standard communication protocol with field display, and can realize the acquisition of voltage, current, active power, reactive power, power factor and power consumption and other parameters with accuracy level up to 0.2. The appearance of multi-functional meter is shown in Fig 3-32, and the technical parameters are shown in Table 3-11. The power consumption of the pump group is calculated by the total power parameters of the system (current, voltage and power) minus the power consumption of the two pumps. The power consumption of the pump unit is obtained by subtracting the power consumption of the two heat pump units from the total system power parameters (current, voltage, power).

Fig 3-32 Electric power data acquisition device

Table 3-11 Pressure sensor technology parameters

Scope of application (V)	Accuracy (level)	Output	Supply voltage (V)
220/380	0.2	RS-485	DC 220

The main function of the data center is to convert the analog signal from the data acquisition base station to digital signal and then realize data acquisition, recording, storage and export through the industrial control computer. The data center includes data acquisition module, Web server (industrial control machine), configuration software, industrial control cabinet, etc. Fig 3-33 shows the structure of the data center, the Web server is installed with configuration software, which has its own database, all monitoring data can be accessed in real time in the local area network, and the data recording time and upload time of the data center can be set arbitrarily.

Data acquisition module is used to realize the conversion of analog signal and digital signal. XSL/A-16 inspector is used, which can realize 16 channels of analog input, and the total number of analog input in this project is 14 channels, and 2 channels are reserved. The inspector adopts RS485 communication interface, ModbusRTU protocol, with display panel, its appearance is shown in Fig 3-34, technical parameters are shown in Table 3-12.

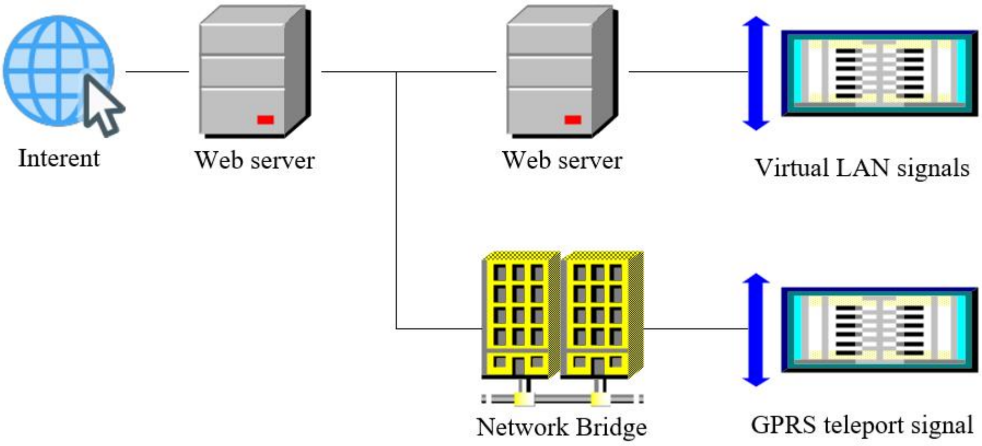

Fig 3-33 Data center structure

Fig 3-34 Appearance of patrol

Table 3-11 Technical parameters of inspected instrument

Accuracy (%)	Number of channels	Input signal (mA/ V)	Operating power (V)
0.25	16	4~20/0~10	DC 24

3.3 Soil temperature field simulation methods

3.3.1 Underground tube heat exchanger heat transfer process

The buried tube heat exchanger can be classified into three forms based on its installation in the ground: horizontal, spiral, and vertical. The horizontal form is suitable for soft soil, but it has disadvantages such as poor heat transfer effectiveness, susceptibility to temperature fluctuations, and a large area requirement, which limits its practical usage. The spiral form has advantages like low installation costs and a smaller footprint, but it faces challenges with U-tube pipe processing, fluid flow resistance, and higher energy consumption, which also restrict its widespread use. On the other hand, the vertical form offers benefits such as a smaller footprint and stable operation, despite requiring a larger initial investment. Due to its space-saving nature and long-term operational stability, the vertical buried tube heat exchanger is commonly employed in practical projects[16].

This paper focuses on the heat transfer performance of the vertical U-shaped buried tube heat exchanger. This heat exchanger is a critical component in soil source heat pump systems, and the accuracy of its heat transfer model directly affects the reliability and precision of calculation results. The chapter aims to analyze the heat transfer process between the U-shaped buried tube heat exchanger and the surrounding soil. In terms of research emphasis, the investigation of heat transfer in outdoor vertical buried tube heat transfer systems can be divided into two main areas: heat transfer within the borehole and heat transfer outside the borehole.

Heat transfer within the borehole primarily examines the heat exchange between the circulating fluid within the pipes and the surrounding filling material. It investigates factors such as the thermal and physical properties of the filling material, the arrangement and quantity of heat exchanger pipes within the borehole (typically single U or double U types), the temperature distribution of the filling material along the pipe, and the impact of hole depth and aperture on the heat exchanger. Additionally, it explores the influence of heat exchanger layout (hole spacing) on underground heat exchange systems, the effects of thermal and physical properties of the circulating pipes on heat exchanger performance, and the enhancement of thermal and physical properties of the circulating pipes and filling materials while maintaining economic feasibility. Extensive research has been conducted on heat transfer through pores [16-19] providing a theoretical foundation for determining design parameters of heat exchange holes and buried pipe structures (e.g., circulating pipe diameter, velocity) as well as optimizing filling materials (e.g., thermal conductivity) in a cost-effective manner.

Heat transfer outside the hole mainly studies the influence of heat change inside the hole through the hole wall on the rock and soil mass outside the hole, which is the theoretical basis for the study of heat exchanger extracting heat from the rock and soil mass or releasing heat to the rock and soil mass. In the operation process of ground source heat pump, how much heat can the rock and soil body outside the hole and the underground water body provide for the heat pump system, or how much storage capacity can be provided for the heat pump system to store its heat release, which is the basis of long-term and stable operation of the system; This is to rely on the heat transfer problem research.

The research on heat transfer in rock and soil mass under the action of ground source heat pump underground heat exchange system, because the influence range is limited to local areas, the rock and soil mass in the influence range is generally regarded as homogeneous body. Therefore, the research on heat transfer calculation of heat transfer holes and rock and soil mass in this field mainly depends on the heat conduction model outside the holes (heat transfer model in rock and soil mass under the action of heat transfer system) and its analytical solution.

The vertical buried tube heat exchanger system consists of a U-shaped buried tube heat exchanger under the ground surface and the circulating fluid inside the tube, the borehole backfill, and the soil around the outside of the borehole. Its heat exchange process consists of six main components as follows:

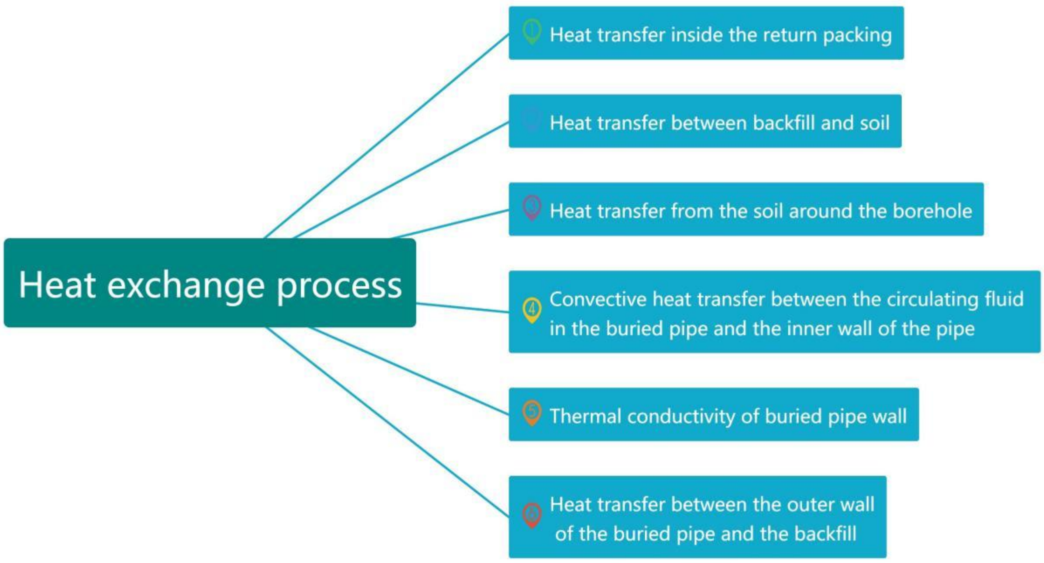

Fig 3-35 Type of heat transfer process of buried tube heat exchanger

Usually the outer wall of the buried pipe and back filler visible close contact, the heat transfer process can be ignored, that is, the temperature of the outer wall of the buried pipe and contact with the back filler layer temperature can be regarded as the same; drilling back filler and soil contact surface thickness can also be regarded as infinitesimal, the heat transfer between can also be ignored, then in the vertical buried pipe heat exchanger heat transfer analysis, generally only consider the following four processes: ① buried pipe circulation fluid and convective heat transfer process inside the tube wall; ② buried pipe wall thermal conductivity process; ③ back filler internal heat transfer process; ④ drilling around the soil heat transfer process.

The heat transfer process of vertical buried tube heat exchanger can be seen in Fig3-36 When the heat pump system is running, the water inside the buried tube is forced to circulate by the circulation pump, and the water inside the tube is forced to convective heat exchange with the buried tube wall. When the heat pump system is shut down, the water stays in the buried pipe, then the water and the buried pipe wall between the natural convection heat transfer. The heat transfer between the fluid inside the buried pipe and the wall of the buried pipe is convection heat transfer, a certain micro-element section ΔZ, whose heat transfer is q1. There is a temperature difference between the inside and outside wall of the buried pipe, and heat conduction occurs, a certain micro-element section ΔZ, whose heat conduction is q2. In the actual project there is a certain amount of moisture in the soil and backfill, and its heat transfer process includes heat conduction and thermal convection in two ways, which is a coupled process of heat and mass transfer. However, the results of previous studies [20] show that the difference in accuracy between the coupled heat and mass transfer heat exchange model and the pure heat conduction model is small. In order to simplify the heat transfer process, in this paper, the heat transfer process of soil and backfill is considered as a pure heat conduction process, and the heat conduction of a certain micro-element section ΔZ, the heat conduction of backfill is q3 in Fig. and the heat conduction of soil q4 in Fig 3-36.

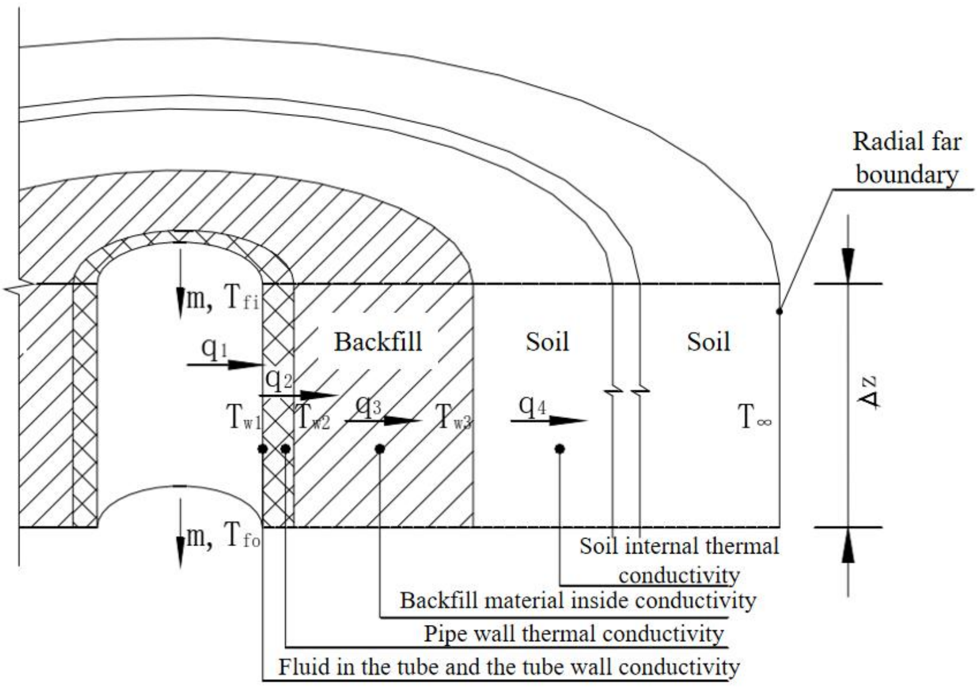

Fig 3-36 Schematic diagram of heat transfer progress of vertical ground heat exchanger

When the heat pump system is stopped, the fluid inside the U-tube, the U-tube, the backfill and the soil are in thermal equilibrium. When the heat pump system is running, forced convection heat transfer occurs between the fluid inside the tube and the tube wall, and the temperature of the fluid inside the tube, the buried tube wall, the return filler and the soil will all change in turn. As the system runs for a longer period of time, the affected soil range will expand, while the soil temperature field in the whole buried tube group area also changes. Therefore, the entire heat transfer process between the buried pipe heat exchanger and the surrounding soil is a non-stationary heat transfer process. Among them, the heat transfer inside the borehole can be considered as steady-state heat transfer after several hours of system operation due to the small geometry and heat capacity when the system operating parameters remain unchanged. In the steady-state heat transfer process, a certain micro-element segment ΔZ, q1=q2=q3.

3.3.2 Analytical solution heat transfer model for buried tube heat exchangers

The analytical solution numerical model is currently one of the most important heat transfer models for buried tube heat exchangers. The analytical solution numerical model is based on the concept of thermal resistance, which is obtained by solving and correcting a set of heat transfer equations, and the heat transfer of a U-shaped buried tube heat exchanger is non-stationary. In the process of this heat transfer analysis, it is generally divided into two parts for analysis outside the borehole and inside the borehole. In the heat transfer analysis of the part outside the borehole, the depth of the borehole is much larger than the diameter of the borehole, the soil outside the borehole can be approximated as an infinite medium or semi-infinite medium, and the U-shaped buried tube can be regarded as a line heat source or column heat source. In the heat transfer analysis of the part within the borehole, including heat transfer between the fluid inside the pipe and the pipe wall, heat conduction inside the buried pipe wall, heat transfer between the buried pipe wall and the backfill, etc., the geometric size and heat capacity of the heat transfer medium is much smaller than that of the part outside the borehole. When the system line for several hours, the heat transfer thermal resistance of the part within the borehole can be considered according to the steady state heat transfer process.

The soil heat transfer process outside the borehole wall needs to be analyzed using a non-stationary heat transfer model. The simplified stratified heat transfer models commonly used at present can be divided into: infinite length line heat source model, finite length line heat source model, and infinite length column heat source model.

(1) Infinite long line heat source model

The infinite-length line heat source model is to approximate the U-shaped buried pipe as a line heat source and line heat sink. The assumptions of the infinite-length line heat source model are as follows:

1) ignore the heat transfer process in the axial direction of the buried pipe and consider only the one-dimensional heat conduction process in the radial direction; 2) ignore the geometric scale of the borehole and approximate the borehole as an infinite linear heat source on the axis; 3) approximate the underground soil as an infinite heat transfer medium with uniform initial temperature; 4) assume that the underground soil has constant physical properties and its thermal properties are uniform and do not change with the change of soil temperature; 5) ignore the surface heat transfer and the flow of underground water; 6) assume a constant heat flow in the pipe.

(2) Finite Long-Term Heat Source Model

In most practical projects, the annual heat transfer to the soil of the buried heat exchanger is not balanced. Such as hot summer and cold winter areas, the summer load is greater than or equal to the winter load, buried heat exchanger in the surrounding soil will be greater than the annual heat gain, long-term operation that will lead to soil heat accumulation phenomenon, which affects the energy efficiency of heat transfer. As long as the buried heat exchanger in the soil heat absorption and exothermic imbalance, underground accumulation of cold heat will cause the average annual temperature of the underground changes. When the system is operated for many years, the soil heat and cold buildup effect will reach equilibrium. The infinite-length line thermal model does not consider the heat transfer at the ground surface as a boundary and cannot address the effect of annual average soil temperature change on the heat transfer performance of the buried tube heat exchanger.

Considering the variation of annual average soil temperature in actual projects, the influence of surface boundary on heat transfer, and the fact that the depth of vertical buried pipe borehole is not infinite, the finite length line heat source model will be more reasonable. The depth of the borehole is taken as the length of the line heat source, and the soil is approximated as a semi-infinite soil medium. Because the theoretical solution of finite-length line heat source is complicated, there are few studies on its analytical solution at home and abroad, establishes the finite line heat source model outside the borehole through Green's function as well as the linear superposition principle [21].

The assumptions of the finite long-line heat source model are as follows:

1. The subsurface soil is approximated as a semi-infinite heat transfer medium with uniform initial temperature;
2. The subsurface soil is assumed to have constant physical properties and uniform thermal properties and does not change with the change of soil temperature;
3. The first type of boundary conditions is adopted and the surface temperature is assumed to be the local annual average temperature and maintained constant. By introducing the concept of point heat source, the temperature field of a finite length line heat source can be regarded as an iteration of the temperature field generated by the point heat source.

As shown in Fig3-37, it is clear from the symmetry that the soil temperature distribution around the linear heat source in the column coordinate system is related to the z-coordinate and the radial coordinate ρ in the axial direction.

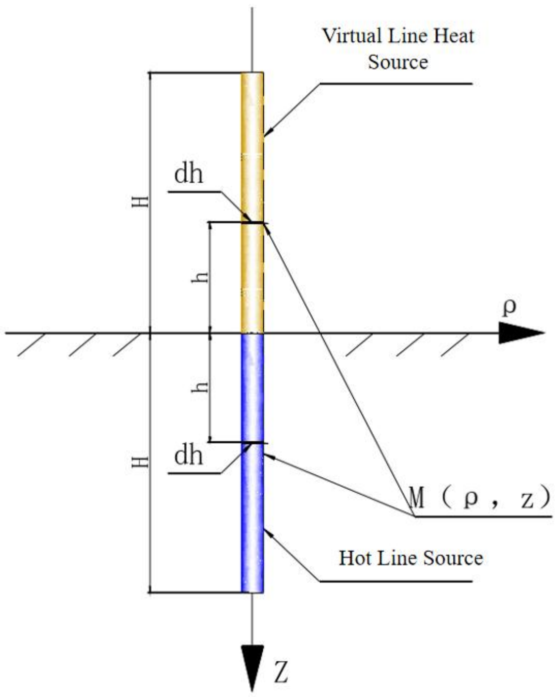

Fig 3-37 Principle diagram of virtual heat source method

The infinite line heat source model is based on the fact that the depth of the U-shaped buried pipe is much greater than the diameter of the borehole, and the U-shaped buried pipe is considered The infinite-length column heat source model approximates the soil as an infinite heat transfer medium. The infinite-length column heat source model approximates the borehole as an infinite cylinder. as an infinite cylinder, the soil around the borehole is also considered as an infinite heat transfer medium, and a constant heat flow is assumed at the borehole wall. A constant heat flow is assumed at the borehole wall. When the system runs for a short time, the infinitely long line heat source model results in a large error, while when the system runs for a long time, the infinitely long line heat source model results in a large error. When the system is operated for a longer period of time, the results of the infinite-length heat source model are similar to those of the infinite-column heat model. Both models Both models ignore the effect of soil as the heat transfer medium and cannot reflect the heat and cold buildup effect caused by the heat and cold imbalance. When the system operation time tends to be infinite, the results obtained will produce some errors. To remedy this drawback, the a finite long-line heat source model that treats the soil around the borehole as a semi-infinite medium has been proposed. This model is closer to the engineering reality and can reflect the actual heat transfer process more accurately, but there are still relatively few related studies.

The interior of the borehole consists of heat transfer media such as backfill, buried pipe wall and fluid inside the pipe, whose geometric scale and heat capacity are much smaller than the exterior of the borehole, so when the system operating parameters remain unchanged, the heat transfer thermal resistance of the system can be considered by the steady-state heat transfer process after a few hours of operation. The early heat transfer models inside the borehole are mainly two types of one-dimensional heat transfer models and two-dimensional heat transfer models. The one-dimensional heat transfer model simplifies the multiple buried pipe branches in the borehole into a single equivalent pipe, thus simplifying the heat conduction inside the borehole to one-dimensional heat conduction. The two-dimensional heat transfer model treats multiple buried pipe branches in the borehole as different heat flows, and the steady-state temperature field in the borehole is the iteration of each heat flow. The above two models fail to reflect the effect of thermal short circuit between buried tube heat exchangers, when the research content needs to consider the thermal short circuit between the tubes, it is necessary to use a quasi-3D model for analysis, that is, on the basis of one- and two-dimensional heat transfer, more in-depth consideration of the change in fluid temperature along the depth direction.

3.3.3 Numerical solution of heat transfer model for buried tube heat exchanger

Numerical solution model is one of the main heat transfer models for buried tube heat exchangers, which is a method of solving by computer with discrete mathematical theory. Compared with the analytical solution method, the numerical solution model has better applicability, such as better solution for nonlinearity, complex geometry, complex boundary conditions, etc. The analytical solution heat transfer model simplifies the geometry in the borehole and has higher accuracy in the long-term operation of the buried tube heat exchanger. Unlike the analytical solution heat exchanger model, the numerical solution model fully considers the internal geometry of the borehole and is more suitable for simulating the heat transfer in buried tube heat exchangers for short periods of time. However, the disadvantage is that it requires longer computational time. The numerical simulation process first determines the differential equations of thermal conductivity, then determines the boundary conditions of the borehole, initial conditions and thermal properties of the soil through certain simplifications and assumptions, and finally solves the numerical model using the finite difference method or the finite element method.

(1) Eskilson Model

The Eskilson model[22] is based on a numerical solution model for a finite long line heat source, solved by a numerical discretization method with finite differences. The model fully takes into account the interaction between boreholes, so it is more accurate for solving the soil temperature field around the buried tube heat exchanger. Because of the large amount of numerical solution data and long computation time, the Eskilson model was used to analyze the temperature distribution of the soil outside the borehole by the G-function method (dimensionless temperature response factor) [23].

The solution of the temperature response factor needs to be performed in two steps. In the first step, two-dimensional explicit finite-difference simulations about the borehole are performed to solve for the heat flow pulse about the step function. In the second step, the temperature response of the configured borehole step function heat flow pulse is determined by three-dimensional iteration. When the response of the temperature of the outer wall of the borehole with time is causeless, its temperature versus time function is the g function. The coefficient of the heat flow impulse temperature response corresponding to each unit step can be obtained using the interpolation g-function method. However, the Eskilson method is not suitable for application to calculations with short time steps.

(2) Yavuzturk model

Yavuzturk et al[24] extended the applicability of the dimensionless influence factor based on the Eskilson model.The Yavuzturk model can be applied to the simulation calculations of heat transfer in buried pipes with short time.

(3) Shonder and Beck model

Shondeer and Beck[25] proposed a factorless heat transfer model that can be discretized and solved using the finite difference method. The model uses a single pipe of equivalent diameter as the diameter of a U-shaped buried pipe. Given the existence of a thin layer of finite thickness around the assumed equivalent diameter single pipe, the heat in the borehole is a one-dimensional heat transfer through the thin layer, the grout, and the surrounding soil. When the heat flow acting on the inner surface of the thin layer and the distal soil temperature are constants, the temperature field around the borehole can be solved by solving for.

Numerical solution is a method based on discrete mathematics and solved by computer. Numerical solution method has strong applicability; it can better solve nonlinear problems, complex boundary condition problems and complex geometric shape problems. At present, the main finite difference method, boundary element method and finite element method are used to solve partial differential equations. In this paper, we mainly use the finite element method.

The finite element method is a numerical method used for solving various problems in engineering[26]. It is widely used in engineering problems such as structural mechanics, fluid mechanics and heat transfer. However, in the process of solving practical problems, it is difficult to express a complete mathematical description, especially the difficulty of determining the boundary conditions and initial conditions, which makes it difficult to get the analytical solution of the equation. Numerical methods can solve the deficiency of differential equations in this respect.

The two commonly used numerical methods are finite element and finite difference, but in order to get a more accurate solution or a solution close to the analytical solution, it is necessary to divide the differential elements small enough. The finite difference method uses a finite difference equation instead of a differential equation equation to produce a set of linear equations. Solving this set of linear equations yields an approximate solution of the equation. Moreover, the finite difference method must be based on a regular difference grid, so the finite difference is more suitable for practical and simple problems. For complex structures and phenomena, the finite element method can be used to discretize them and then apply the interpolation function to solve them at each node. The nodes are used to represent the segmented microelements, and the nodal temperatures are calculated to represent the temperature values of the microelements [27]. In fact, the finite element method is a generalization and summary of the classical approximation calculation. It overcomes both the drawback that the classical differential equations cannot solve the analytical solution of complex problems and the finite difference does not consider the influence between cells. The finite element method is now one of the most commonly used methods in computer simulation calculations.

3.3.4 Simulation Software Introduction

Currently, Computational Fluid Dynamics (CFD) technology is widely used in numerical simulation studies to build models for actual conditions, perform simulation prediction analysis, and thus pre-optimize the design of complex real-world projects, and then make technical recommendations for later design and construction. Fig 3-35 shows the workflow diagram of CFD[28]. The heat exchange process between the subsurface heat exchanger and the surrounding soil studied in this chapter can be implemented using numerical simulation software for computational fluid dynamics. The temperature change trend of the soil in the depth direction can be obtained very clearly by means of computer numerical tools. Changes in the temperature field around the heat exchanger can also be observed. Therefore, the numerical calculation in this chapter is done using CFD, and the whole simulation process is divided into three steps. The simulation process is divided into three steps.

1. Using the pre-processing modeling function, the entire underground heat exchanger structure is modeled according to the actual dimensions, including the single U-shaped pipe, the borehole, the backfill area, and the surrounding soil.

2. Use Ansys' own meshing software to draw the mesh and define the corresponding structural area as well as the inlet and outlet of the pipe.

The inlet and outlet of the medium inside the pipe are set.

3. The drawn mesh file is transferred to the Ansys post-processing software fluent, and the initial conditions and other parameters are set.

After convergence of the results, the results are processed to obtain the curves and temperature field clouds.

In this paper, we simulate the heat transfer between the underground pipe cluster and the soil to determine the soil temperature distribution around the underground pipe cluster after one year of operation of the ground source heat pump system, so as to analyze the underground soil temperature distribution after 30 years.

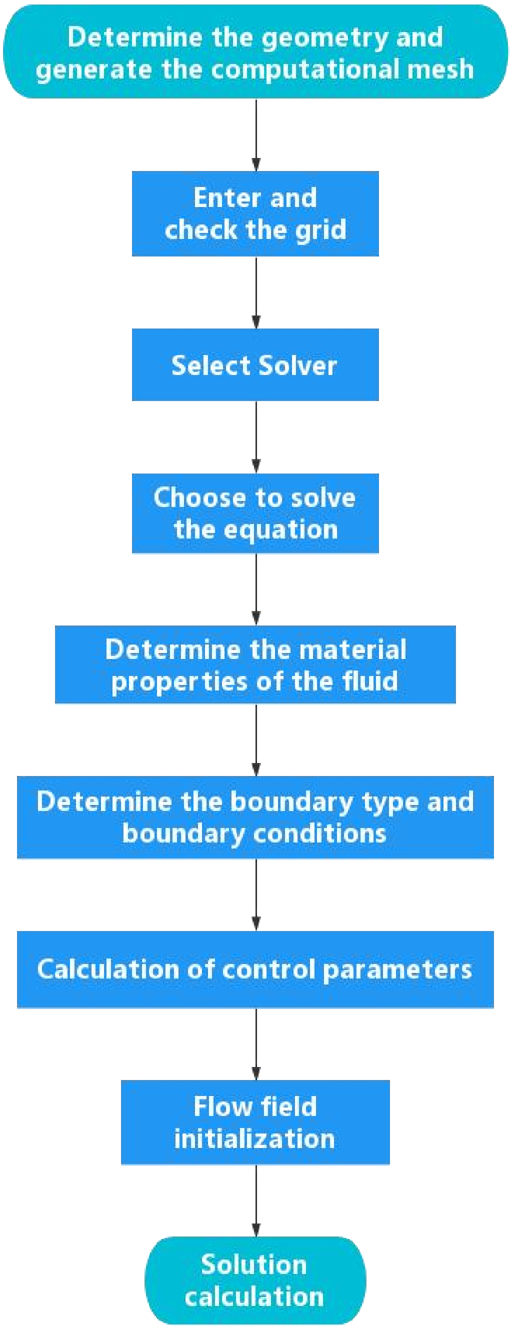

Fig 3-35 The working process of CFD

Fluent is a widely used software in China that is based on the finite volume method. It has a wide range of capabilities including incompressible and compressible fluid calculations, flow field simulations, laminar and turbulent flow simulations, multiphase flow analysis, porous media analysis, heat transfer and thermal mixing analysis, solid and fluid coupled heat transfer analysis, and more. It supports various reference systems and can be used for 3D flow, 2D axisymmetric, and 2D planar analysis[29].

GAMBIT, on the other hand, is a pre-processor for Fluent. It allows users to import software mesh models and 3D geometry models. The mesh features in GAMBIT are highly flexible, and unstructured meshes can be used to handle complex flow shapes[30].

The simulation solution process in Fluent can be divided into four steps[31]. First, the governing equations of fluid dynamics are established. Second, the boundary conditions and initial conditions for the calculation are determined based on the specific research model. The third step involves grid generation, where the model is divided into discrete points to establish the control equations. Finally, the discrete equations are solved to obtain the approximate solution of the studied object. Convergence of the solution is crucial, and special attention should be given to ensure convergence. If the solution does not converge, the discrete equations need to be rebuilt and the calculation conditions adjusted until a convergent solution is achieved.

Fluent excels in simulating turbulence problems in engineering. It includes various turbulence models, which are mathematical relationships used to model turbulence[32]. Turbulence is prevalent in most flows in nature, and Fluent provides the tools to address turbulence-related challenges. However, selecting the appropriate turbulence model is important as different fluids may require different models. Turbulence models are based on certain assumptions and may not be universally applicable across all fluids. Careful consideration and evaluation are necessary to choose the most suitable turbulence model for a specific fluid.

3.3.5 Build the model

(1) Simplification of the model

In the heat transfer problem of the ground source heat pump system, several simplifying assumptions are made to model the soil part outside the borehole[22]. These assumptions help to reduce computational complexity and provide a clearer research problem. The following assumptions have been made in this study:

Heat flux uniformity: It is assumed that the heat flux is the same within the same cross-section of the subsurface soil around all boreholes.

Uniform soil thermal properties: The thermal properties of the subsurface soil, such as thermal conductivity, remain uniform and do not change with temperature.

Neglecting atmospheric convection: Heat transfer between external atmospheric convection and the soil is not considered in the analysis.

Pure thermal conductivity: Heat transfer between the soil and buried pipe is considered to be a pure thermal conductivity process, and it is assumed that it is not affected by moisture migration.

Negligible heat transfer between boreholes: The spacing between boreholes is assumed to be large enough that the heat transfer between them can be neglected.

Neglecting contact heat resistance: The contact heat resistance between the soil and the backfill material is neglected.

Uniform initial temperature: The initial temperature of the subsurface soil is assumed to be uniform and consistent, and the ambient temperature is not considered to disturb the ground temperature.

These assumptions simplify the heat transfer model and help in obtaining reasonable approximations and insights. However, it is important to note that these assumptions may introduce some level of error, and the actual project conditions should be carefully considered in practical applications.

(2) Model Building

In this study, the heat exchange borehole group was modeled to include various components such as the U-shaped pipe, the borehole, the backfill area, and the surrounding soil. The simulation focused on the distribution of the planar temperature field, and therefore, two-dimensional models were created using the Gambit software[33].

For the simulation study, a rectangular well group was selected with buried pipe spacing of 4 m, 5 m, and 6 m. These well sets were arranged in a 4x4 grid pattern, resulting in 16 buried pipe heat exchangers evenly distributed within the models. To obtain a comprehensive soil temperature distribution map, a distance of 6 m was left around all three models.

The ratio of the borehole area to the land area for the pipe clusters with 4 m, 5 m, and 6 m spacing was 0.002826, 0.002232, and 0.001808, respectively. This information provides an indication of the relative coverage of the borehole area compared to the overall land area.

The specific model maps, illustrating the arrangement of the well sets and the surrounding area, can be found in Figure 3-36. These maps visually represent the layout and configuration of the simulated heat exchange borehole group for the different pipe spacing scenarios.

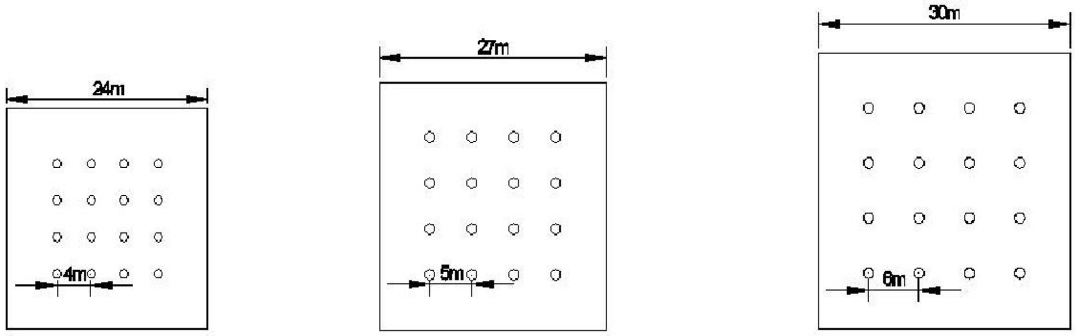

Fig 3-36 schematic of the geometric model

In the simulation process, the grid plays a crucial role in discretizing the model and accurately calculating the soil temperature. The division of the grid is a critical step after establishing the model. While denser grids generally yield better results, they also require more computational time. Therefore, it is important to apply different grid quantities in different locations based on the characteristics of temperature and fluid velocity changes.

Fluent is a software based on finite volume method that allows incompressible and compressible fluids to be calculated in a variety of reference systems, flow field simulations, laminar and turbulent flow simulations, constant and non-constant flow analyses, multiphase flow analyses, porous media, heat transfer and thermal mixing analyses, coupled solid and fluid heat transfer analyses, solid and fluid coupled heat transfer analyses, etc. Select the FLUENT5/6 solver and define the circulating water as "Fluid" and the HDPE pipe, backfill material and soil as "Solid". Define the inlet of the buried pipe as "VELOCITY INLET", the outlet as "OUTFLOW", and the other boundaries as "WALL". Export the model mesh file and read it into the FLUENT solver for calculation. In the FLUENT solver, first check the mesh with the "check" command, and smooth the mesh if necessary. Then define the solver as "Pressure Based", "Implicit" and select the "k-epsilon(2eqn)" model. After that, the mathematical model, the material parameters for different zones, the cell zone conditions, the boundary conditions about fluid zone, etc., are set up.

To ensure accurate results and efficient computation, the number of grids should be increased in areas where significant temperature and fluid velocity changes occur. On the other hand, in areas where the changes are slower, the number of grids can be reduced. For instance, around the pipe wall where the temperature field changes dramatically, a denser grid should be applied. Conversely, in areas outside the soil where the temperature field changes less dramatically, a sparser grid can be used.

The specific results of grid division based on temperature field characteristics are illustrated in Figure 3-37. This figure provides a visual representation of how the grid distribution varies in different regions of the model based on the temperature field changes. By adapting the grid density to the local temperature field variations, the simulation can achieve accurate and efficient calculation of the soil temperature distribution.

In the last step of the modeling process, it is important to define the boundary conditions for the established model. These boundary conditions ensure that the model recognizes the external boundaries and enables the specification of specific calculation values when importing the model into Fluent. In the case of a two-dimensional model, there are two boundary conditions for the three models:

Outer soil edge boundary (Wall-1): This boundary condition represents the outer boundary of the soil. It defines the behavior of the soil at the outer edges of the model. The specific calculation values for this boundary condition need to be set according to the desired conditions or constraints of the system.

Borehole wall boundary (Wall-2): This boundary condition represents the wall of the borehole. It defines the behavior of the soil at the walls of the borehole. The specific calculation values for this boundary condition need to be set based on the characteristics and properties of the borehole wall, such as the heat transfer coefficient or temperature.

By defining these boundary conditions, the model in Fluent will be able to simulate the heat transfer and temperature distribution within the soil, taking into account the interactions at the outer soil edges and the borehole walls.

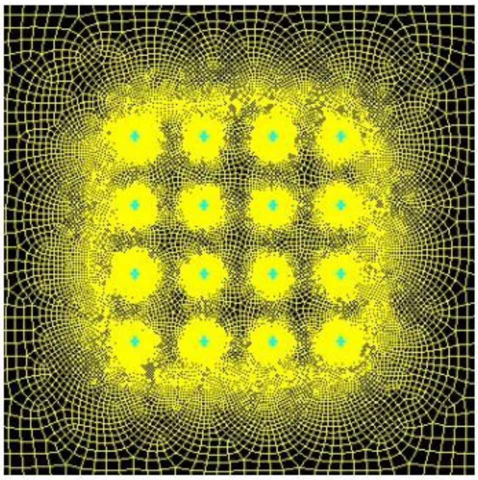

Fig 3-37 Grid computing area

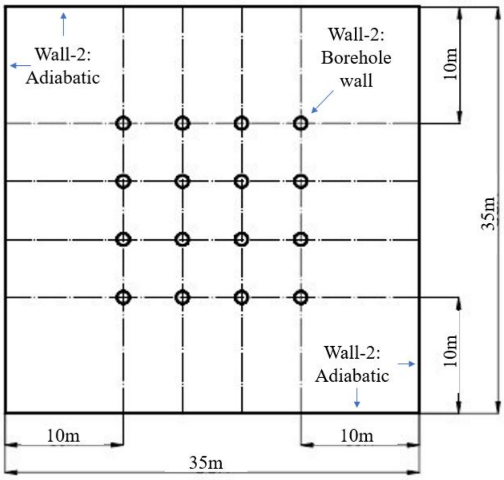

Fig 3-38 Boundary Conditions

Before starting the Fluent calculation, several setup steps need to be performed. Here is an overview of the key setup tasks:

Mesh Verification: Verify that the mesh is of good quality and does not contain any negative elements. Use the check option to identify any issues and ensure the mesh is suitable for the simulation. If necessary, redefine the length of the mesh using the size scale option.

Mathematical Model: Choose the appropriate mathematical model for the simulation, considering factors such as fluid flow, heat transfer, and turbulence. Select the relevant equations and models to accurately represent the physical phenomena involved in the heat transfer process.

Material Parameters: Set the material parameters for different zones in the model. Define the properties of the soil, borehole, and any other materials present in the simulation. This includes thermal conductivity, density, specific heat, and other relevant properties.

Internal Zone Conditions: Specify the conditions within the internal zones of the model. This may involve setting initial temperature distributions or other relevant parameters specific to the heat exchanger or surrounding soil.

Cell Zone Conditions: Set the conditions for individual cell zones within the model. This allows for differentiation of properties or behaviors within specific regions of the model, if necessary.

Fluid Zone Boundary Conditions: Define the boundary conditions for fluid zones in the model. This includes specifying the temperature, pressure, flow rate, or other relevant parameters at the boundaries.

Soil Outer Boundary Conditions: Since the influence of heat transfer at the far boundary of the soil on the heat exchanger is weak, it is often set to adiabatic conditions. This means that no heat transfer occurs at the outer boundary, and temperature fluctuations can be disregarded.

Iteration and Calculation: Determine the number of iterations or convergence criteria required for the calculation. Start the numerical calculation of the soil temperature field using Fluent. Monitor the convergence and ensure that the calculation progresses accurately.

By following these setup steps, you can prepare the Fluent simulation for calculating the soil temperature field and obtaining the desired results.

Model Assumptions

Since the heat transfer between the vertical U-shaped buried tube heat exchanger and the surrounding soil is related to the type of this soil, water content, thermal parameters, and the accumulated heat and cold load of the building, the following assumptions are made when establishing the model for the convenience of the solution:

1.The calculated physical parameters of the soil are averaged over the entire heat transfer process;

2. The initial temperature of the soil is assumed to be uniform;

3. Parameters such as soil density, thermal conductivity, and specific heat do not change with changes in soil temperature and depth;

4. The heat migration in the soil due to moisture migration is ignored, i.e., the heat transfer between the soil and the buried pipe is assumed to be purely conductive.

Boundary Conditions

In this paper, the influence of the change of ground surface temperature on the soil temperature around the well cluster is not considered, and the soil thermostatic zone is taken at the depth of 20-40m on the ground surface, and the temperature of the thermostatic zone is taken to be 2-6℃ higher than the annual average temperature of the region, and below the thermostatic zone, the soil temperature increases in a gradient of 0.03℃/m. In the calculation area of the well cluster, the first type of boundary conditions, i.e. constant temperature, is at the peripheral boundary;

Type II boundary conditions at the pipe wall:

$$-\lambda \frac{\partial T}{\partial r}\Big|_{r=0.032} = q \tag{3-3}$$

Approximately, q is considered as a constant value.

The heat exchange between the buried pipe and soil per unit area, i.e., the heat flow density q, is:

$$q = \frac{Ql}{F} \tag{3-4}$$

Where: Q - heat release to the soil per unit length of buried pipe; F - surface area of the buried pipe underground, m.

Basic parameters

The initial parameters required for the simulation were obtained through thermal response experiments and field surveys, and the initial soil temperature was 8.31° C. Since the project site belongs to a severe cold region with low winter temperature, an antifreeze glycol solution was selected as the flow medium in the buried pipe. The basic parameters are shown in Table 3-12.

Table 3-12 Soil thermal property parameters

Original soil temperature (℃)	Soil heat transfer coefficient W/(m·℃)	Soil density (kg/m³)	Specific heat capacity of soil J/(kg·℃)	Ethylene glycol thermal conductivity W/(m·℃)	Ethylene glycol density (kg/m3)	Specific heat capacity of ethylene glycol J/(kg·℃)	Heat transfer (w/m)
8.31	2.573	2200	950	0.442	1050.33	3603	25

3.3.6 Numerical calculation of the control equation

The choice of the model in the simulation is important because different computational models can produce different computational results. In this chapter, the number The computational model chosen for the value calculation in this chapter is the standard K-ε model. This model has been widely accepted in practical applications for a long time, and the results obtained by this calculation model are more accurate[34] .

According to the numerical solution finite element theory basis, the model is discretized, the discretization is to divide the whole into a finite number of tiny units, the more accurate the unit division, the closer the calculation result is to the accurate value[35]. For the problem of subsurface temperature field, we can use the finite element method to solve it. The temperature of any micro-element in a certain area can be discretized to the node of the cell, i.e., the temperature of the node Tij is used to represent the temperature of this micro-element. By using Gambit's own meshing function, the cells are divided into moderately sized meshes around the buried pipe to meet the needs of the calculation.

If the region A is divided into B cells and n nodes, the temperature field is discretized into T1, T2, T3 ....Tn node temperatures. If L of them are known boundary temperatures, the temperature values to be found are n-L.

$$J = \sum_{e=1}^{E} J^e$$
(3-5)

Therefore, it is actually a multivariate function, so that the change problem is actually transformed into a multivariate function to find the extreme value of the problem. That is:

$$\frac{\partial J}{\partial T_k} = 0 \quad k = 1,2,3,\ldots,n-1 \tag{3-6}$$

Substitute (3-5) into (3-6)

$$\frac{\partial \sum_{e=1}^{E} J^e}{\partial T_k} = \sum_{e=1}^{E} \frac{\partial J^e}{\partial T_k} = 0 \quad k = 1,2,3,\ldots,n-1$$
(3-7)

Eq. (3-7) is the (n-L) algebraic equation from which T1, T2, T3,... are solved. . Tn-L, etc. n-L unknown variables.

The instantaneous temperature field becomes of the following form, assuming that there are unknown quantities Tk,

$$\begin{bmatrix} K_{11} & K_{12} & \dots & K_{1n} \\ K_{21} & K_{22} & \dots & K_{2n} \\ \dots & \dots & \dots & \dots \\ K_{n1} & K_{n2} & \dots & K_{nn} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ \dots \\ T_n \end{bmatrix} + \begin{bmatrix} n_{11} & n_{12} & \dots & n_{1n} \\ n_{21} & n_{22} & \dots & n_{2n} \\ \dots & \dots & \dots & \dots \\ n_{n1} & n_{n2} & \dots & n_{nn} \end{bmatrix} \begin{bmatrix} \partial T_1 / \partial t \\ \partial T_2 / \partial t \\ \dots \\ \partial T_n / \partial t \end{bmatrix} = \begin{bmatrix} P_1 \\ P_2 \\ \dots \\ P_n \end{bmatrix}$$

k=1,2,3,... .n

(3-8)

Or it can be abbreviated as：

$$[K]\{T\} + [N]\left\{\frac{\partial T}{\partial t}\right\} = \{P\} \tag{3-9}$$

In the formula,

[K]- the temperature stiffness matrix;

[N]-the variable temperature matrix;

[P]-right end column vector.

For any moment t we have:

$$[\mathrm{K}]\{\mathrm{T}\}_{\mathrm{t}} + [\mathrm{N}]\left\{\frac{\partial \mathrm{T}}{\partial \mathrm{t}}\right\}_{\mathrm{t}} = \{\mathrm{P}\}_{\mathrm{t}}$$

(3-10)

The initial and boundary conditions are given when solving for the unstable temperature field. $\{\frac{\partial T}{\partial t}\}_t$is the unknown quantity, the backward differential for time yields:

$$\left\{\frac{\partial \mathrm{T}}{\partial \mathrm{t}}\right\}_{\mathrm{t}} = \frac{\{\mathrm{T}\}_{\mathrm{t}} - \{\mathrm{T}\}_{\mathrm{t}-\Delta \mathrm{t}}}{\Delta \mathrm{t}} \tag{3-11}$$

Substituting (3-10) into (3-11) yields

$$\left([\mathrm{K}] + \frac{1}{\Delta \mathrm{t}}[\mathrm{N}]\right)\{\mathrm{T}\}_{\mathrm{t}} = \frac{[\mathrm{N}]}{\Delta \mathrm{t}}\{\mathrm{T}\}_{\mathrm{t}-\Delta \mathrm{t}} + \{\mathrm{P}\}_{\mathrm{t}} \tag{3-12}$$

Equation $\{\mathrm{T}\}_{\mathrm{t}-\Delta \mathrm{t}}$ is the known initial temperature field, the temperature field at time t from the (3-12) formula, and then iterative method, the temperature field for each moment$\{\mathrm{T}\}$.

Combining the above theoretical analysis and the research in this paper, we use the numerical simulation method to establish the two-dimensional unsteady heat transfer model of the buried tube heat exchanger by using the numerical solution model developed based on the cylindrical heat transfer model to meet the basic situation of the actual project.

The heat exchanger is symmetrically arranged in the soil in the form of the differential equation for thermal conductivity in column coordinates as:

$$\rho C_P \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) \tag{3-13}$$

where，T—transient temperature of the soil，℃；Cp—soil specific heat capacity，J/kg • ℃；ρ —density，kg/m^3； λ —thermal conductivity of soils，W/m • ℃；t—system runtime，s；

r—radius of distribution of temperature field, m; x—symmetric axis coordinates, m.
For soil thermal conductivity processes outside the borehole:

$$\frac{\partial T}{\partial \tau} = \frac{\lambda_g}{\rho_s c_s}\left(\frac{\partial^2 T}{\partial Xx^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad (3\text{-}14)$$

Where, λ_s—thermal conductivity of backfill material,W/m • ℃ ρ_s—density, kg/m^3 c_s—specific heat capacity,$J/(kg \cdot °C)$ T—soil temperature, ℃ τ—time, s

The circulating medium in the U-tube is circulated in the heat pump unit using the power of the water pump, so the heat transfer between the circulating medium and the tube wall is the forced convection heat transfer. A large convective heat transfer coefficient, which is necessary for effective heat transfer, can only be achieved when the medium in the tube is in a turbulent state. The parameters for building the k-epsilon(2eqn) turbulence model are shown in Table 4. Then define the solver as "Pressure Based", "Implicit" and select the "k-epsilon(2eqn)" model. Turbulent flow is a state of fluid motion in which the fluid exhibits irregular and chaotic vortex motion. The turbulent state is essential for achieving large convective heat transfer coefficients. It effectively promotes heat transfer and heat transfer efficiency by increasing fluid mixing, expanding heat transfer surface area, breaking boundary layer restrictions, and reducing heat transfer resistance. The medium in the U-shaped tube can be assumed to be incompressible fluid. The forced flow heat transfer of the circulating medium during the operation of GSHPs can be described by the continuity equation (3-15); the momentum equations (3-16), (3-17), and (3-18); and energy equation (3-19).

The main basis of the continuity equation is that the amount of fluid entering the control body should be balanced with the amount of variation throughout the region. The equation is as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (3\text{-}15)$$

The momentum equation is mainly based on Newton’s second law and the law of the conservation of momentum. This equation can express the combined forces on the fluid in motion using the rate of change in momentum. In the study of fluid microclusters, the force inside the fluid is much larger than the gravitational force exerted from outside, so the gravity factor is not considered to simplify the calculation, which is expressed as follows:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = \upsilon\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) - \frac{1}{\rho}\frac{\partial p}{\partial x} \quad (3\text{-}16)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = \upsilon\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) - \frac{1}{\rho}\frac{\partial p}{\partial y} \quad (3\text{-}17)$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = \upsilon\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) - \frac{1}{\rho}\frac{\partial p}{\partial z} \quad (3\text{-}18)$$

The energy equation is established on the basis of energy conversion and the law of conservation of energy. The equation mainly reflects the idea that the energy of the inflow and outflow of microelements is conserved, which is expressed as:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}) \quad (3\text{-}19)$$

where x, y, and z are the right-angle coordinates in three coordinate directions, m; u, v, and w are the flow velocities in three right-angle coordinate directions, s; ρ is the density, kg/m^3; t is the time, s; v is the dynamic viscosity, Pa-s; P is the pressure on the fluid micro-element, Pa; T is the temperature, and k; the is thermal diffusivity, m^2/s.

Table 3-13 k-epsilon(2eqn) turbulence model parameters.

Cum	C1-Epsilon	C2-Epsilon	TKE Prandtl number	TDR Prandtl number
0.09	1.44	1.92	1	1.3

3.4 Performance simulation methods

3.4.1 Introduction of TRNSYS17 simulation software

TRNSYS (Transient System Simulation Program) is a powerful software tool developed by the Solar Energy Laboratory (SEL) at the University of Wisconsin-Madison. It has undergone refinement and enhancement by various research centers and institutions worldwide, including the Thermal Energy Research Center (TESS) in the United States, the Solar Energy Research Center in Germany, and the Centre de Recherche en Technique et de Recherche Scientifique de la Construction in France. TRNSYS is widely used for dynamic simulation of a wide range of systems.

The version used in this paper is TRNSYS17, which has been developed and improved over the past 20 years, making it a mature and widely adopted simulation system. It is a fully scalable and modular transient simulation tool that offers powerful capabilities and flexibility. It is utilized by researchers and engineers worldwide, particularly in the field of new energy sources. TRNSYS17 is known for its open-source code, which allows third-party editing using programming languages like C, FORTRAN, and PASCAL[36].

The TRNSYS software is commonly applied in the study and simulation of various systems, including radiant floor heating systems, water source heat pump systems, ground source heat pump systems, cogeneration, low energy consumption buildings, air conditioning systems, fuel cell systems, and solar energy utilization[37]. For HVAC applications, TRNSYS provides specific modules such as the ground source heat pump program, energy storage program, and the HVAC program's Tess module[38]. These modules enable dynamic simulation of ground source heat pump system operation.

In this paper, the Simulation Studio and TRNBuild software packages within TRNSYS17 are used for building model construction[39], calculation of annual time-by-time cooling and heating loads of buildings, simulation of annual and year-by-year changes in average underground temperature of ground source heat pump systems, and simulation of system COP (Coefficient of Performance) changes. The Simulation Studio interface, shown in Fig3-38, serves as the primary platform for building simulation models. It allows researchers to select and integrate the required modules to construct the simulation platform for building models and ground source heat pump systems[40].

Overall, TRNSYS17, with its extensive capabilities and modular structure, provides a valuable tool for conducting detailed and accurate simulations of various systems, aiding in the analysis and optimization of system performance in the context of energy efficiency and renewable energy utilization.

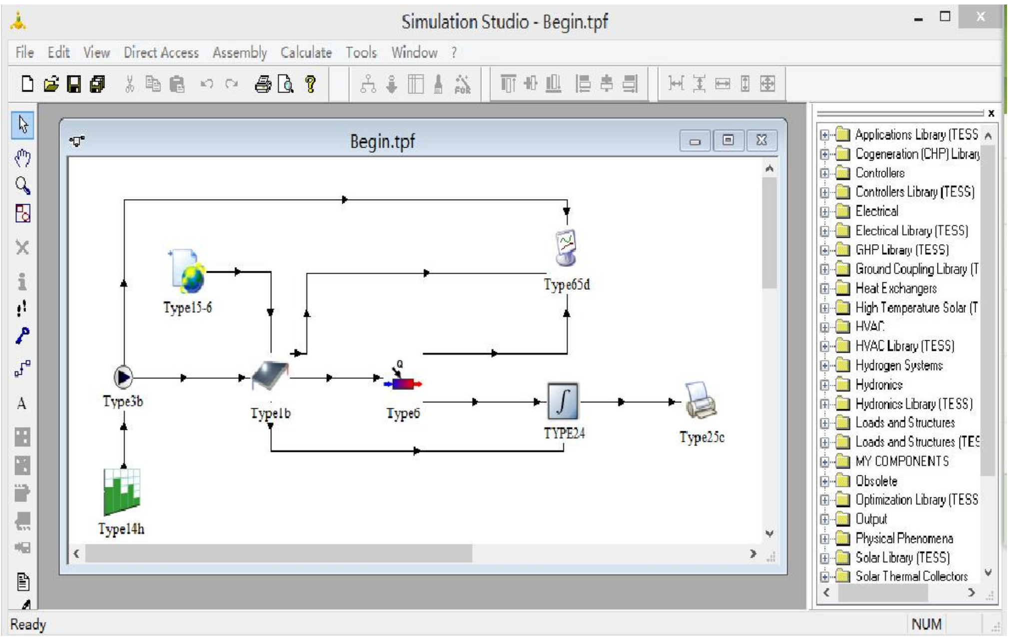

Fig 3-38 Operation interface of Trnsys17

3.4.2 Main modules and mathematical bases

Modularity is the main feature of the TRNSYS software, and in this paper, the simulation of the annual time-by-time cooling and heating loads, the simulation of the average subsurface temperature, and the simulation of the energy efficiency of the heat pump unit of the target project are mainly achieved by connecting and calling modules of the buried pipe heat exchanger system, heat pump unit, and meteorological data [41]. The important theoretical bases covered in this section are: the integrated explicit finite difference method (FDM) based on the G-function algorithm[42] and the superimposed temperature algorithm based on the numerical method analytic method to calculate the heat transfer process in the buried tube heat exchanger module; the functional relationships of the parameters in the heat pump module and the COP algorithm, the differential equations for the energy variation of the room load, and the energy, continuity, and momentum equations. And briefly introduce the role of important modules.

(1) Underground tube heat exchanger module

The vertical buried tube heat exchanger heat storage model uses the g-function method for the numerical analysis of heat transfer. g-function algorithm was originally developed by Swiss researchers Eskilson, Hellstron, and others in the 1980s and 1990s [43]. It is widely accepted internationally and is based on the superposition principle.

The g-function approach has several advantages over other numerical analysis methods. First, it requires less computational time than mathematical modeling methods for three-dimensional nonstationary thermal conductivity that involve discrete numerical calculations. This efficiency makes the g-functional algorithm more suitable for engineering applications where time is a critical factor.

Second, the g-functional approach is more scientifically rigorous than semi-empirical design formulas that rely on the concept of thermal resistance. These formulas estimate the required buried pipe length based on thermal and cooling loads, but may oversimplify the system. In contrast, the g-functional algorithm is more adaptable to complex conditions and avoids oversimplification.

Overall, the g-function approach used in the vertical buried pipe heat exchanger module provides a time-saving and scientifically rigorous method for analyzing heat transfer. It strikes a balance between computational requirements and engineering practicality, making it a widely recognized and accepted method internationally.

The G-function algorithm for the buried tube heat exchanger problem combines numerical and analytical solutions to accurately calculate the temperature response of a single borehole under constant heat flow conditions. The algorithm then utilizes the superposition principle to determine the temperature response of a buried tube heat exchanger consisting of multiple boreholes under varying loads.

Several software platforms have been developed based on this approach, such as EED, TRNSYS, and GLHEPRO, created by Lund University in Sweden, the Solar Energy Laboratory at the University of Wisconsin-Madison in the USA, and the University of Oklahoma in the USA [44]. In addition, domestic software developers, as well as some universities and colleges, have also created buried tube heat exchanger calculation software using this method.

The TYPE557a buried pipe heat exchanger model, also known as the DST (Duct Ground Heat Storage) heat storage model, represents a vertical heat transfer model that is symmetric about the center, treating the buried pipe and the surrounding soil as a column heat source[45]. In this model, heat transfer occurs through conduction between the buried pipe, the backfill material, and the soil, while convection takes place between the medium inside the buried pipe and the pipe wall.

The TYPE557a model places the vertical buried pipe heat exchanger uniformly within the heat storage body. The overall heat transfer and local heat transfer are obtained using the explicit finite difference method (FDM). The FDM divides the overall heat transfer process into a two-dimensional grid, with a vertical coordinate (j) and a radial coordinate (i). The vertical thermal conductivity is represented by $K\tau$, and the radial thermal conductivity is represented by Kr.

By combining the FDM method with the analytical solution of the stable fluid part, the average storage temperature in the subsurface (referred to as the Average storage temperature) is determined through superposition, considering both the overall heat transfer and the local heat transfer[46]. This approach enables a comprehensive analysis of the heat transfer process in the buried pipe heat exchanger system.

Radius direction, and vertical direction (i-1, j), (i, j) heat fluxes between two adjacent nodes:

$$F_r(i,j) = K_r(i,j) \cdot [T(i-1,j) - T(i,j)] \tag{3-16}$$

$$F_\tau(i,j) = K_\tau(i,j) \cdot [T(i-1,j) - T(i,j)] \tag{3-17}$$

with Qsf (i, j) ,denotes the local heat exchange endothermic source at node,   Q1 (i, j),for the medium circulation generated heat exchange within the heat accumulator, it is obtained that：

$$T(i,j)_{t+\Delta t} = T(i,j)_t + [F_r(i,j) - F_r(i+1,j) + F_z(i,j) - F_z(i,j+1) + Q_1(i,j) + Q_{sf}(i,j) \cdot \Delta t / C(i,j)\,] \tag{3-18}$$

The local temperature Tl satisfies the radial thermal conductivity equation:

$$C\frac{\partial^2 T_l}{\partial t} = \lambda\left(\frac{\partial^2 T_l}{\partial r^2} + \frac{1}{r}\frac{\partial T_l}{\partial r}\right) - q_l \quad r_b < r \le r_l \tag{3-19}$$

The temperature change in the subregion k during the overall heat exchange is：

$$\Delta T_g = \frac{q_l t_g}{C} = \frac{E_k}{CV_k} \tag{3-20}$$

Temperature of the stable flow in the annular area around the buried pipe:

$$T_{sf} = (T_g{}^k - T_{g,i,j}{}^k) \cdot \frac{r_1{}^2}{2l^2} \cdot h(\frac{r}{r_1})$$

(3-21)

$$h\left(\frac{r}{r_1}\right) = \frac{1}{2}\left(\frac{r}{r_1}\right)^2 - ln\left(\frac{r}{r_1}\right) - \frac{3}{4} \tag{3-22}$$

Finally the temperatures are superimposed according to the superposition principle for the overall heat transfer temperature, the local heat transfer temperature and the temperature of the stable fluid:

$$T = T_{g,i,j}{}^k + T_{1,j'}{}^k + T_{sf,j'}{}^k \tag{3-23}$$

where Tg, Tl, and T sf are the overall, local, and steady fluid temperatures, respectively.

(2) Heat pump unit module

Type927 is a single-stage heat pump Water-Water Heat Pump (WHP) module[47], which serves to form a heat transfer between the circulating mass on the buried pipe side and the circulating mass on the load side. The model simulates a heat pump unit with two modes of operation, heating and cooling, which are similar to the actual heat pump in terms of temperature control and are controlled by user-input control signals for mode switching.

The heat production and power consumption of the heat pump are expressed through the relationship between the evaporator and condenser inlet fluid temperatures, which is a function of the heat source side and load side inlet temperatures, and thus simplify the heat pump model with the function[41]:

$$Q_{hp} = f_1(T_{ci}, T_{ei}) = a_1 + b_1 T_{ci} + c_1 T_{ei}$$

(3-24)

$$P_{hp} = f_2(T_{ci}, T_{ei}) = a_2 + b_2 T_{ci} + c_2 T_{ei}$$

(3-25)

Where: Q_{hp} - heat pump heat production, kW; P_{Ph} - heat pump power consumption, kW; Tc i - heat pump heat production, kW; Te i - heat pump heat production, kW; a1, b1, c1 - heat pump heat production fitting coefficients; a2, b2, c2 - heat pump power fitting coefficients.

The COP of the heat pump unit under winter conditions is calculated [48] as follows:

$$COP = \frac{Cap_{heating}}{P_{heating}} \tag{3-26}$$

Where: Capheating - heat supply under actual working condition, unit kJ/h; Ph eating - power consumption of heat pump under actual working condition, kJ/h.

where the circulating fluid draws heat from the soil:

$$Q_{absorbed} = Cap_{heating} - P_{heating} \quad (3\text{-}27)$$

Both sides of the heat pump, i.e., the heat source side and the load side of the outlet water temperature calculation formula is

$$T_{load,out} = T_{load,in} - \frac{Cap_{heating}}{m_{load}Cp_{load}} \quad (3\text{-}28)$$

$$T_{source,out} = T_{source,in} - \frac{Q_{absorbed}}{m_{source}Cp_{source}} \quad (3\text{-}29)$$

Where: Tsource,in - heat pump unit heat source side inlet water temperature, ℃; Tl oad,in - heat pump unit load side inlet water temperature ℃; Cps ource - heat pump unit heat source side circulating fluid specific heat, kJ/(kgK); Cpi oad - heat pump unit load side circulating fluid specific heat, kJ/(kgK); ms ource - heat pump unit load side water flow, kg/s ml oad - heat pump unit load side water flow, kg/s.

(3) Modules for circulation pumps

Type 3d is a pump module that maintains the mass flow rate at the fluid outlet so that it is constant and powers the fluid in the buried pipe heat transfer process and on the load side, without considering its pressure drop in the calculation. The flow rate of the circulation pump is calculated by[49]:

$$G = \frac{860Q}{\Delta T} \quad (3\text{-}30)$$

Where: G - circulation pump flow rate, 3m/h; Q - system heat exchange, W; T - supply and return water temperature difference, ℃.

(4) Other Modules

Type 9c is the Data Reader module of TRNSYS software, which can read data from external files and process them according to the specified time step, and then connect them to other components, which can be perfectly interfaced with various software, and can seamlessly import the calculated load data or the actual load data. This paper is mainly used to read the annual time-by-time hot and cold load data. TRNSYS software can recognize various formats of weather data such as EPW, TMY, TMY2, TMY3, TXT, etc., which is applicable to a wide range of applications and can be perfectly interfaced with weather software. The paper adopts tmy2 format for the Changchun area, including dry and wet bulb temperature, radiation, relative humidity, moisture content, etc. Type 515 is the time converter for the cooling and heating seasons in TRNSYS software. This converter uses the signal input of the whole year as the conversion method, which can realize the control conditions of heating phase, cooling phase and equipment shutdown period.

3.4.3 System model construction

The process of building the model involves analyzing the actual system and determining the required modules and their relationships, inputting the necessary parameters based on the real-world conditions, and connecting the components according to the actual system process. In this study, the models include load calculation models for estimating yearly time-by-time cooling and heating loads, as well as system models for simulating ground source heat pump systems.

To construct these models, certain assumptions need to be made, similar to those made in formula calculations and other software applications. These assumptions are based on a thorough understanding and analysis of the software and model, as well as the relationship between individual components and system characteristics. The assumptions are formulated scientifically and reasonably, taking into account both major and minor contradictions within the study. Some of the key assumptions include:

Assumption of constant thermal properties: Assuming that the thermal properties of the fluid in the system remain constant during operation.

Neglecting heat loss in connecting piping: Ignoring heat loss in the piping of the system's connecting sections.

Stability of equipment parameters: Assuming the stability of various parameters of the heat pump system's equipment units during operation and long-term use.

Uniform distribution of fluid temperature and velocity: Assuming uniform distribution of temperature and velocity in the pipe's cross-section.

Uniform indoor room temperature: Assuming uniform room temperature in rooms of the same functional use within the building, as well as a uniform initial temperature of the soil.

Simplified soil characteristics: Neglecting the variation of mission-type parameters in the soil due to water migration and considering the subsurface soil as an isotropic medium.

Assumption of good thermal contact: Assuming pure thermal conductivity between the soil and the buried pipe, neglecting the contact thermal resistance between the pipe wall and the filler.

The simulation model for the ground source heat pump system includes various components such as the buried pipe heat exchange system, building load side, water-water heat pump machine, circulating water pump, signal controller, data input module, data output module, and other relevant modules. These modules are regarded as physical components, and the actual engineering characteristics and details mentioned in the previous part are strictly input into each module. Table 3-13 presents the module models, module names, and corresponding functions of the main components in the ground source heat pump system model.

In the previous part of Chapter 2, detailed descriptions of the theoretical basis and mathematical foundation of each major component, such as the buried pipe heat exchanger, heat pump unit, and building load calculation, were provided. In this section, the focus is on the actual case study of the ground source heat pump system, including organizing parameter data and importing it to establish connections within the system. The simulation model of the ground source heat pump system includes several components that will be used in the simulation. These components are the heat pump unit, buried pipe heat exchanger, signal controller, meteorological parameters, pumps, building load side, calculator, and output devices. The selection of these components is based on the equipment chosen for the system and its operational conditions.

The simulation model of the ground source heat pump system is constructed by connecting these components as shown in Fig 3-39. The model takes into account the interactions and relationships between the different components and simulates the operation of the system based on the input parameters and data. By establishing this simulation model, it becomes possible to analyze the performance and behavior of the ground source heat pump system under different operating conditions, assess its energy efficiency, and evaluate its ability to meet the building's cooling and heating demands.

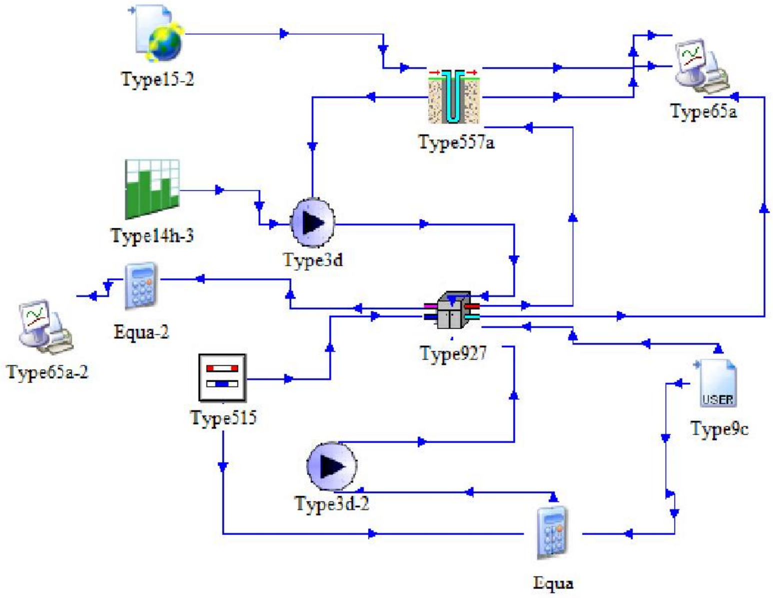

Fig 3-39 The establishment of simulation model of soil source heat pump

In the buried pipe heat exchanger module TYPE557a involves a total of 42 parameters, mainly the depth of the borehole, horizontal buried pipe depth, soil thermal conductivity, buried pipe diameter, backfill thermal conductivity, buried pipe thermal conductivity, etc., in which the U-shaped pipe is selected high-density polyethylene pipe, buried pipe circulation fluid selected glycol antifreeze solution the density of the solution is 1050kg/m^3 heat transfer coefficient of 0.442W/(m ℃), borehole depth 100m, borehole diameter 0.18m, the comprehensive thermal conductivity of the soil around the buried pipe is 2.573W/(m K), there is no gap between the backfill and buried pipe, the density of the underground rock and soil is 2500kg/m^3, the initial temperature of the top of the thermal storage body is set to 8.31℃ according to the soil thermal response test. Where the storage volume (Storage volume) is calculated as

$$StorageVolume = \pi \times NumberofBoreholes \times BoreholeDepth \times (0.525 \times BoreholeSpacing)^2$$

In Type927 heat pump unit module mainly deals with the heat pump power and its correction at different inlet and outlet temperatures, the number of heat pumps, flow rate, etc. and allows to import the actual heat pump settings and parameters, in the form of external files, into the components of the heat pump. The system runs from October 25 to April 15 for a total of 4164h under heating conditions, from April 16 to May 31 for a total of 1104h during the transition season, from June 1 to August 31 for a total of 2208h under cooling conditions, and from September 1 to October 24 for a total of 1284h during the transition season.

Table 3-13 The main components of soil source heat pump system model

Module Model	Module Name	Module Function
Type557a	Underground tube heat exchanger	Heat storage model for buried pipes and surrounding soil

Type927	Heat pump units	Single-stage heat pump water-water heat pump unit
Type 3d	Circulating water pump	Fixed speed water pump
Type 9c	External file reading module	Read external load data files
Type 15-2	Meteorological parameter reading module	Read weather data in TMY2 format
Type 515	Signal Controller	Time converter for the cooling and heating season
Type 65a	Output Devices	Online data file export and plotting
Equa	Calculators	Data calculation and equation tools
Type56	Building load side	Building model calculation output load file

Type 15-2 in Fig3-39 is the import module for weather data. Since the weather data for Changchun, the region where the building is located, is obtained by METEONORM software in the first chapter, it is only necessary to use this module to import the third-party TMY2 format weather data extracted in METEONORM software in the form of external files into the soil source heat pump model according to the geographical location of the building, to connect the The required temperature data, etc. are connected as needed to ensure the integrity of the module.

The building load side module Type56 seamlessly imports the load data calculated in the building load model created using TRNBuild into the calculation model for the average subsurface temperature and heat pump energy efficiency of the ground source heat pump.

The weather parameters are input into the building module and the buried pipe system module, and the feedback signal from the building is used to control the heat pump unit module, and finally the calculated annual time-by-time cooling and heating loads, the energy efficiency ratio of the heat pump unit, and the supply and return water temperature of the buried pipe system and the average temperature of the underground heat storage body are formed into output files.

3.5 Summary

In this chapter, we provide an overview of their research topics, including basic information, data sources, and simulation methods for the analysis of soil temperature fields and ground source heat pump performance.

First, we introduce the basic situation of the research subject, various parameters of the building, as well as the composition and various parameters of the ground source heat pump, and at the same time, we introduce the working principle of the self-compensating ground source heat pump by using the area compensation technique to achieve the cooling and heating load balance of the research subject. The meteorological software METEONORM was used to obtain the climatic parameters of Changchun City, the location of the project, to lay the foundation for the next research work.

Secondly, we present the scope and methods of application using CFD software to model the soil temperature field for studying the variation of the soil temperature field in a self-compensating ground source heat pump system during long-term operation.

Finally, we present the simulation method for the performance study of ground source heat pump systems, introduce the use of TRNSYS software, and build the system operation performance model, as well as provide a detailed explanation of the modules used in the model.

This chapter provides a comprehensive description of the research topic, the data sources utilized, and the simulation methods employed to study the soil temperature field and ground source heat pump performance. The use of METEONORM software to obtain climate parameters and the use of CFD and TRNSYS software for modeling and analysis highlight the comprehensive approach taken by the researchers.

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Chapter 4

STUDY OF SOIL HEAT BALANCE OF GSHPS

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4.1 Content

Soil temperature field is considered to be the key to the operational stability of Large-scale GSHP[1-3]. Large-scale GSHP require hundreds of heat exchange holes for heat exchange, and after long-term operation, thermal interference phenomena exist between the heat exchange holes[4], leading to changes in the underground thermal environment and affecting the efficiency of GSHP[5]. Meanwhile, in actual use, the installation of heat exchange holes takes up a lot of space, which also limits the promotion of GSHP technology[6].In northern Canada, where most buildings are dominated by heating demand, the heating and cooling loads are unbalanced[7], resulting in lower soil temperatures after long-term operation, affecting system performance factors and ecology[6]. Therefore, it is important to grasp the changes in the heat exchange hole spacing and soil thermal environment of Large-scale GSHP in long-term operation to ensure the safe and efficient operation of the system.

The project is located in Changchun, a cold region of China. The building is a demonstration project of the National Twelfth Five-Year Plan research project, In order to monitor the operation of GSHP in real time and study the changes of soil temperature field at different underground depths, a monitoring platform of GSHP and a soil temperature monitoring well with a depth of 100m were designed before the implementation of the project. Combined with the monitoring platform, the monitoring data of unit performance and underground soil temperature were studied and analyzed. Meanwhile, the CFD software is used to simulate the influence of the heat exchanger hole on the underground soil temperature under different spacing conditions after the system has been operated for 30 years, and an optimization scheme for the spacing of heat exchanger holes in cold regions is proposed. This study provides the first-hand real-time monitoring data of the operation of GSHP in cold regions, as well as the temperature field change data of different depths of underground soil for 8 consecutive years.

4.2 Introduction

GSHP began to be used in China in the 1980s, and the number of buildings using GSHP increased rapidly in the following years[8-10]. Zhi. J.L et al.[11] simulated the variation of soil temperature during GSHP operation in three cities in cold regions of China to demonstrate the stability of the system over 10 years of operation. You T et al. [12] pointed out the main causes of soil thermal imbalance, including lower soil temperature, lower system performance, lower reliability, system failure, etc. As an important factor restricting the development of GSHP in severe cold areas, the imbalance of soil heat intake and release directly leads to the decrease of soil temperature. Qian and Wang[13] have simulated the heat balance of GSHP in four different working conditions in the heating season and the cooling season. The heat pump only runs in summer when the cooling load is 50kW. After 10 years of long-term operation, the soil temperature changes from 17.5 ℃ to 39.1 ℃. The heat pump only runs with a heat load of 50 kW in winter, after 10 years of long-term operation of the system, the soil temperature gradually decreased from 17.5 ℃ to 6.9 ℃. Yu and Liu [14] simulated the change of soil temperature in a residential building in Beijing during 10 years of operation of GSHP, and found that the soil temperature changes and the temperature difference decreases by 3 ℃ under the condition of seasonal load balance between winter and summer. Under the condition that the intermittent operation of the system in summer led to the imbalance of seasonal load in winter and summer, the soil temperature decreased by about 4.5℃. You and Wang[15] took three cities of Shenyang, Changchun and Harbin as examples to simulate that after 10 years of operation of GSHP without heat compensation, the soil temperature decreased by 10.9℃, 11.7℃ and 11.6℃ respectively. After using the heat compensated GSHP, the soil temperature remains stable, effectively solving the problem of soil temperature imbalance. Shang et al.[16] observed that due to the decrease of soil temperature, the heat exchange rate and the heat pump COP both decreased significantly, and the compressor power increased. After 12 h of operation, COP decreased about 0.6 ~ 0.8. Liu et al.[17] analyzed a GSHP system in a cold area, whose annual heating and cooling loads were 818,228 kW/ h and 192,351 kW/ h, respectively. Soil temperature and borehole inlet and outlet temperature showed a decreasing trend in 10 years. In the second year, the COP of system efficiency decreased dramatically due to the well medium temperature below 0℃.

Studies have found that the performance of the buried pipe heat exchanger has a great impact on the GSHP and soil heat balance[18], and a good borehole layout is very important for soil temperature recovery, which is closely related to the contact area of the surrounding soil and the appropriate distance between the buried pipes[19]. Retkowski et al. [20] simulated the GSHP system and analyzed the average soil temperature changes at three different distances around. The results show that the temperature drop near the borehole is more serious. The maximum temperature drop after 25 years is 12℃. Gultekin et al. [21] simulated and studied the effect of heat exchange hole spacing on heat transfer efficiency. The heat exchange hole distances of different distances were studied and the best distance was determined[22, 23]. However, increasing the distance between buried pipes will increase the land area and lead to an increase in the initial investment of the project, which is difficult to achieve in densely populated cities[24, 25].

4.3 Analysis of soil temperature monitoring data

The analysis of the data results from the ground source heat pump (GSHP) system monitoring system for the soil temperature variation data collected from the 7th to the 8th year of GSHP system operation was selected for the period from October 2019 to April 2021. Three sets of heat exchange boreholes with different spacing were selected for comparison: monitoring borehole 1 with a spacing of 4 m, monitoring borehole 2 with a spacing of 5 m, and monitoring borehole 3 with a spacing of 6 m. Soil temperature variation at different depths in these monitoring boreholes was studied.

The variation of soil temperature is shown in Figures 4-1, 4-2, and 4-3. it can be seen that the soil temperature in the heat exchange holes at distances of 4 m, 5 m, and 6 m showed consistent periodic fluctuations. The maximum range of temperature variation was observed at a depth of 2.5 m. This is due to the fact that at shallow subsurface levels, soil temperature is strongly influenced by solar radiation. As the depth increases from 10 to 100 m, the range of variation in soil temperature decreases and becomes more stable.

At a depth of 2.5 m, soil temperature peaks in October and troughs in May. In contrast, at depths between 10 and 100 m, soil temperature peaked in November and trough in July. This lag in soil temperature change indicates a lag of about two months for shallow soil temperatures and about four months for deep soil temperatures. This indicates that the thermal diffusion capacity of the soil is weak and heat transfer takes a longer time.

The analysis showed that the soil temperature could not be fully recovered during the transition period of two to three months. However, after 8 years of continuous operation of the GSHP system, the maximum temperature difference in soil temperature measurements ranged from 0.13°C to 0.51°C. This indicates that the soil temperature was effectively recovered, suggesting that the zonal thermal compensation technique can solve the problem of soil heat imbalance and extend the service life of the system in cold regions.

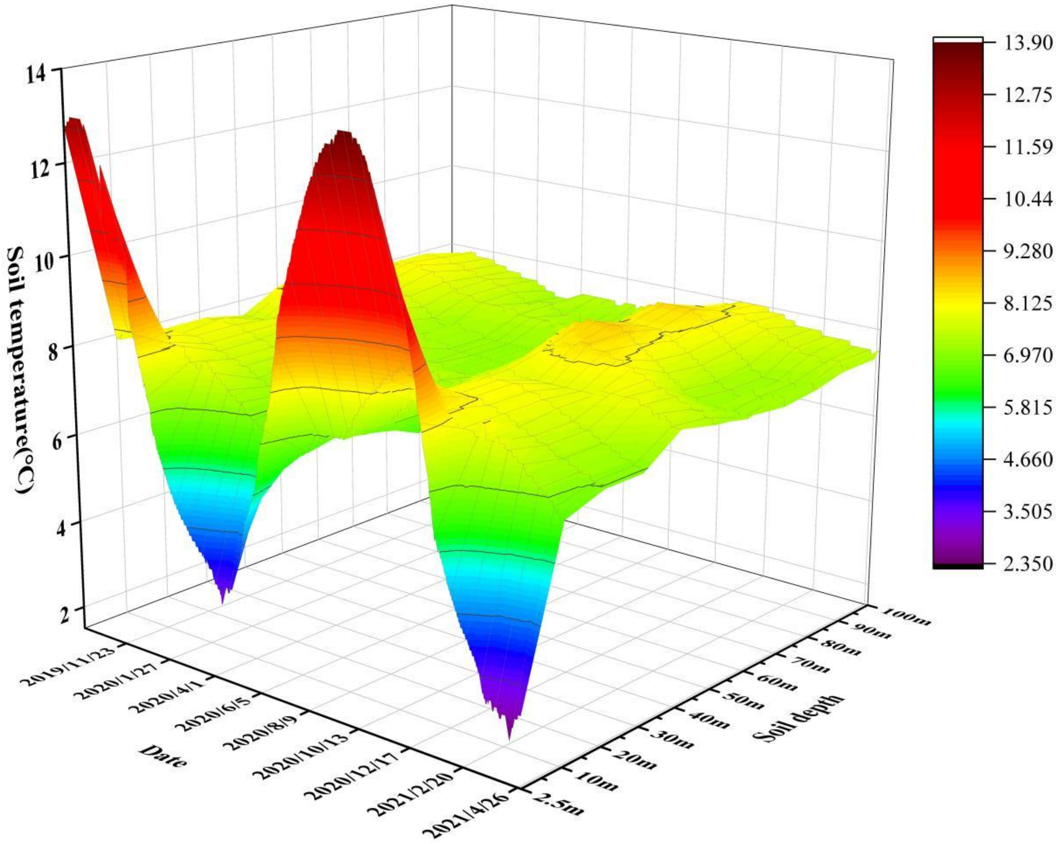


Fig 4-1Soil temperature changes in 4 m interval Wells from September 2019 to April 2021

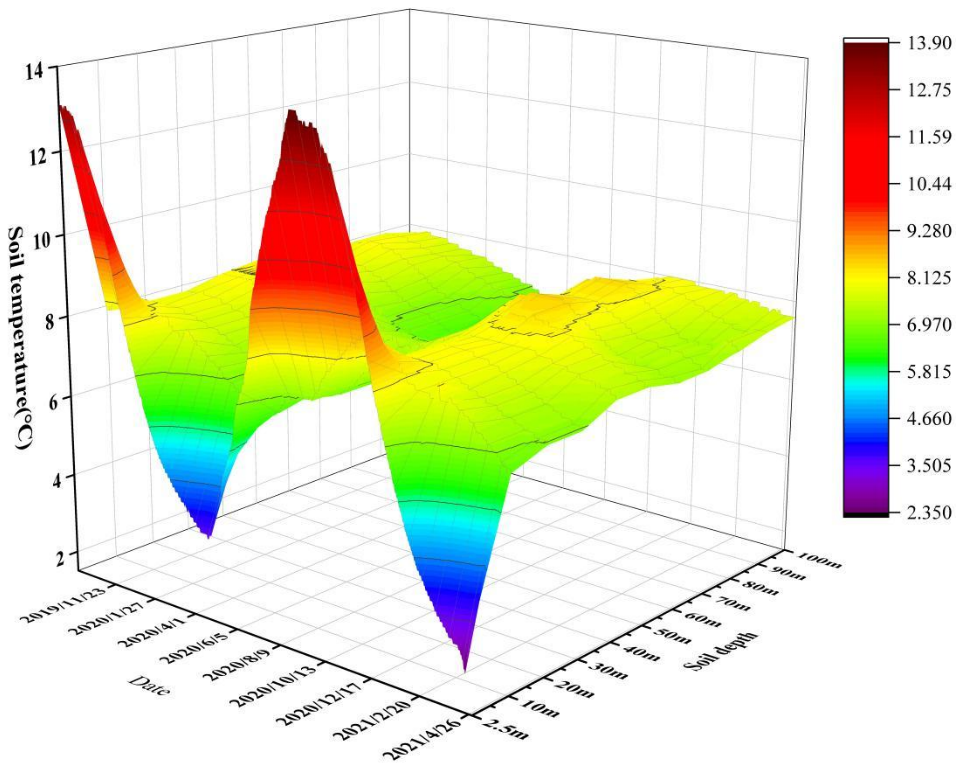


Fig 4-2 Soil temperature changes in 5 m interval Wells from September 2019 to April 2021

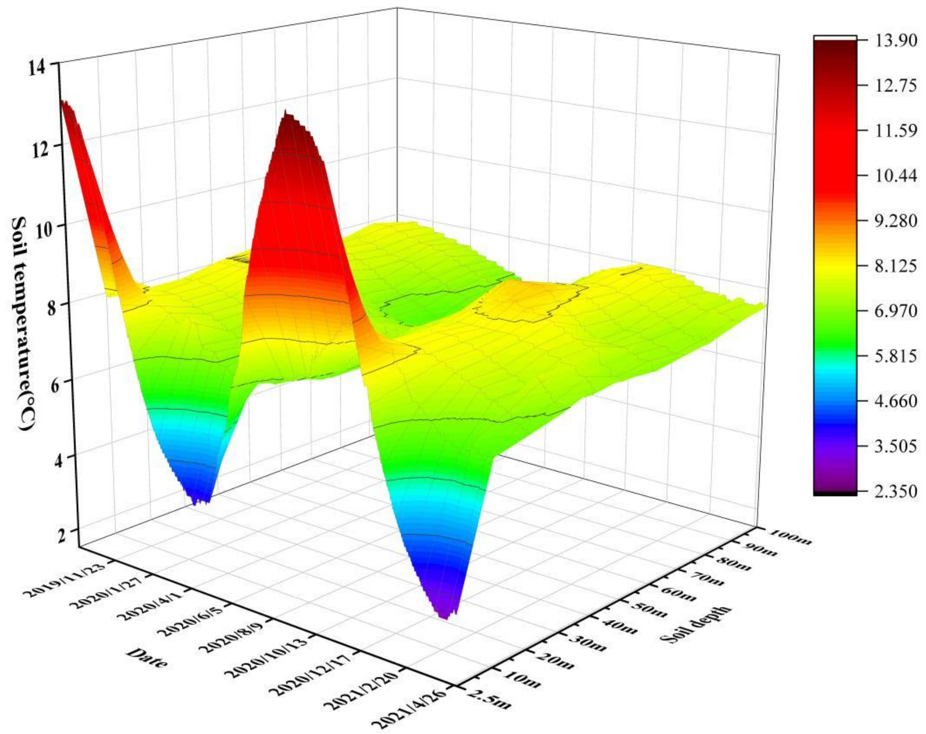


Fig 4-3 Soil temperature changes in 6 m interval Wells from September 2019 to April 2021

Based on the recorded monitoring data, an analysis was conducted on the average soil temperature changes at various depths surrounding the heat exchanger holes, comparing them to the initial soil temperature. The findings are illustrated in Fig 4-4.

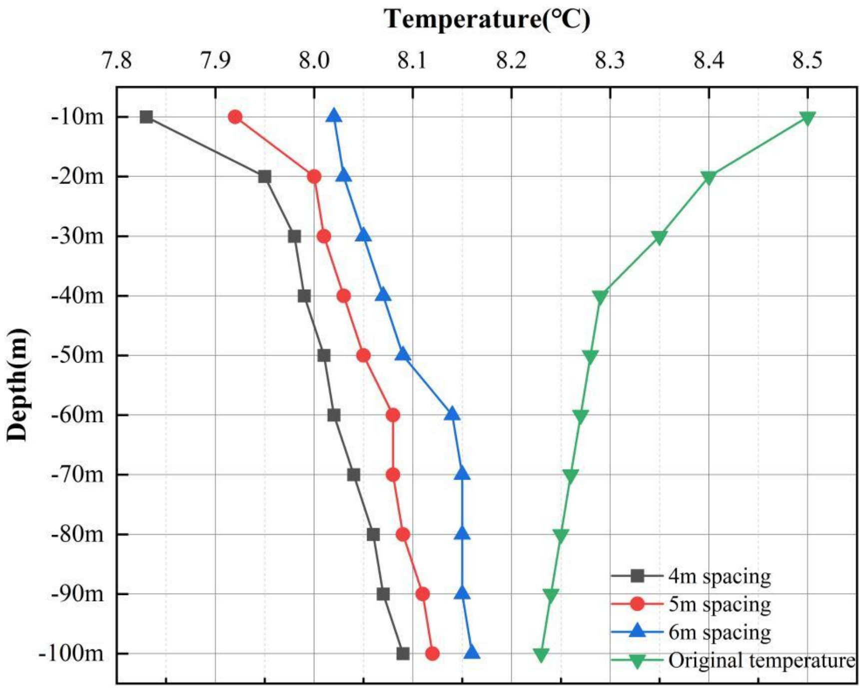


Fig 4-4 Soil temperature changes after the end of the heating period in April 2021

From the figure, it is evident that the soil temperature of the well group with 4m heat exchanger hole spacing experienced a decrease ranging from 0.13℃ to 0.51℃. Similarly, the well group with 5m pipe spacing witnessed a decrease in soil temperature ranging from 0.05℃ to 0.37℃. As for the well group with 6m heat exchange hole spacing, the temperature decrease ranged from 0.02℃ to 0.38℃. The maximum decrease in soil temperature for the 4m, 5m, and 6m heat exchange hole groups was found to be 2.78%, 2.28%, and 2.02% respectively. Notably, the differences in soil temperature change among the different spacing well groups were not significant.

Consequently, these findings suggest that when designing and constructing GSHP systems in cold regions, the use of 4m heat exchange borehole spacing can be considered as it allows for efficient land use within limited project areas. By opting for this spacing, the system can achieve substantial soil temperature changes without compromising performance, thereby optimizing the utilization of available land resources.

4.4 Analysis of simulation results

4.4.1 Analysis of the simulated operation of the system throughout the year

Taking into consideration the specific climatic characteristics of the Changchun area and the load patterns of buildings, the simulation process was divided into four distinct stages, each reflecting different seasonal conditions.

The first stage encompasses the heating period, which spans from October 25 to April 15.

During this stage, the system operates to provide heating to the buildings in response to the colder climate.

Following the heating period, the simulation transitions to the second stage, known as the natural recovery period. This stage extends from April 16 to May 31 and represents the time when the system ceases active heating operations. Instead, it allows the underground heat exchange to naturally restore thermal equilibrium as the weather gradually becomes milder.

The third stage represents the cooling period and occurs from June 1 to August 31. In this phase, the GSHP system shifts its focus to providing cooling to the buildings, adapting to the warmer temperatures characteristic of the summer season.

Lastly, the simulation proceeds to the fourth stage, which corresponds to the natural recovery period after the cooling period. This stage spans from September 1 to October 24, allowing the system to passively recover and reach a state of thermal equilibrium as the climate transitions to cooler temperatures once again.

By dividing the simulation process into these four stages, the model effectively captures the distinct operational requirements and variations in demand throughout the year, considering both heating and cooling needs while allowing for natural recovery and thermal balance during transitional periods.

Fig 4-5 showcases the changes observed in the soil temperature field following the operation of the heat pump for one month, commencing on October 25, 2011. Within the area of the heat exchanger arrangement, the heat exchanger's heat extraction from the soil induces a temperature reduction, resulting in a temperature difference ranging from 0.45℃ to 2.25℃ compared to the initial soil temperature. Specifically, in the immediate vicinity of the heat exchanger, the temperature drop ranges from 2℃ to 2.25℃, indicating a more substantial impact. As we move away from the heat exchanger arrangement, the temperature drop becomes slightly smaller, mostly around 0.5℃.

Moreover, outside the designated heat exchanger arrangement area, the soil experiences fewer effects from the heat absorption of the heat exchanger, leading to smaller temperature changes. The figure also demonstrates that due to the relatively short operational time of the system, the influence of each individual heat exchanger on the surrounding soil temperature remains confined to a limited scope. Mutual interference between heat exchangers has not yet become apparent, suggesting that at this early stage, their effects on each other are negligible.

This observation highlights the initial stage of the system's operation, where the impact on soil temperature distribution is still localized and independent. As the system operates over a more extended period, the thermal interactions and potential interferences between heat exchangers may become more prominent and necessitate further investigation.

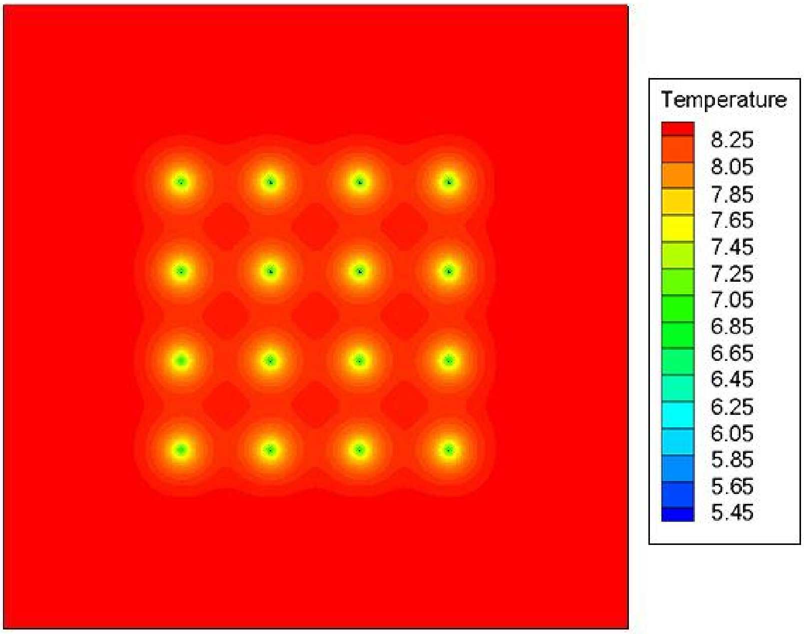


Fig 4-5 The soil temperature change during October 25 to November 25

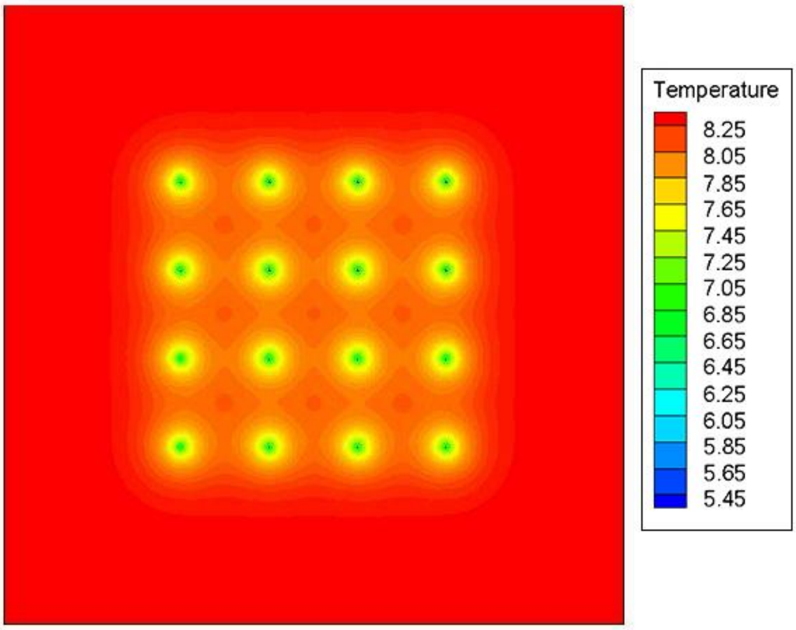


Fig 4-6 The soil temperature change during November 26 to December 25

Fig 4-6 presents the distribution of the soil temperature field between November 26 and December 25, following one month of system operation, corresponding to a total of two months of continuous operation. The figure reveals a consistent decrease in soil temperature within the well cluster arrangement area, with a range of approximately 0.35°C to 2.45°C.

Notably, the impact of the heat exchangers on the soil temperature field is becoming more pronounced. As the system operates, the thermal influence expands, resulting in the emergence of thermal disturbances between the heat exchangers within the tube cluster. These disturbances indicate the beginning stages of thermal interference and interactions among the heat exchangers.

The observed soil temperature decrease and the expanding influence of the heat exchangers signify the progressive establishment of a thermal network within the soil. The interplay between the heat exchangers leads to a complex thermal environment that warrants further investigation to understand the dynamics and potential implications for system performance and efficiency.

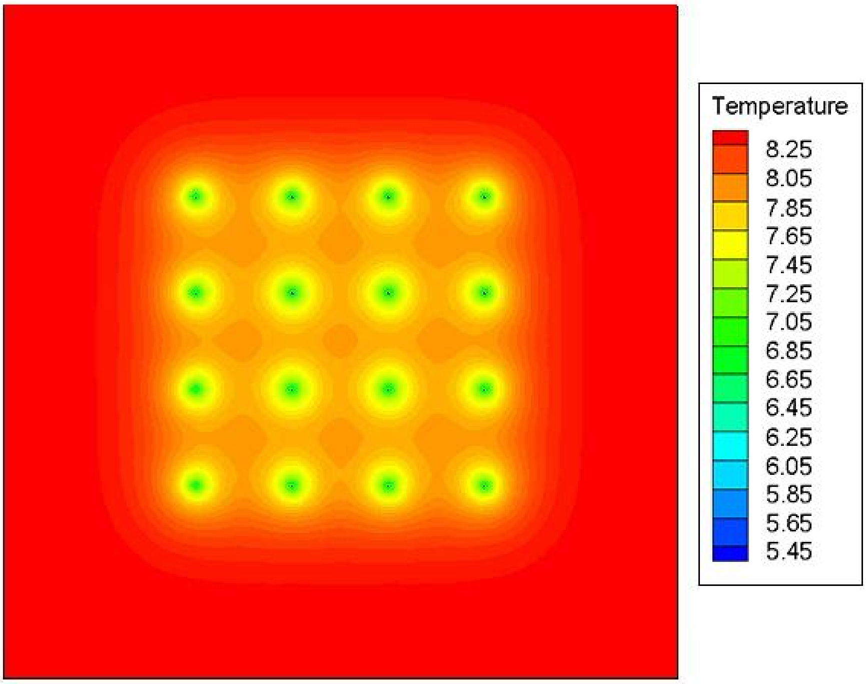


Fig 4-7 The soil temperature change during December 26 to January 25

Fig 4-7 exhibits the soil temperature field between December 26 and January 25, following one month of system operation, indicating a cumulative operation period of three months. The figure demonstrates an ongoing decline in soil temperature, ranging from approximately 0.45°C to 2.65°C.

Furthermore, the influence of the heat exchangers on the soil temperature continues to expand. Specifically, the four heat exchangers situated at the center of the tube cluster persistently absorb heat, causing a substantial drop in the surrounding soil temperature, which reaches a value of 282.35 K. Notably, the heat exchangers positioned at the periphery of the tube cluster exhibit increased interference with one another, suggesting a heightened level of thermal interaction and mutual influence.

These observations emphasize the evolving dynamics of the thermal system as it progresses through three months of operation. The continued decrease in soil temperature, along with the expanding effects of the heat exchangers, highlights the complex nature of the thermal network within the soil. The interplay between the heat exchangers, particularly the intensified interference among those located at the periphery of the tube cluster, underscores the need for a comprehensive understanding of the thermal interactions to optimize system performance and mitigate potential complications.

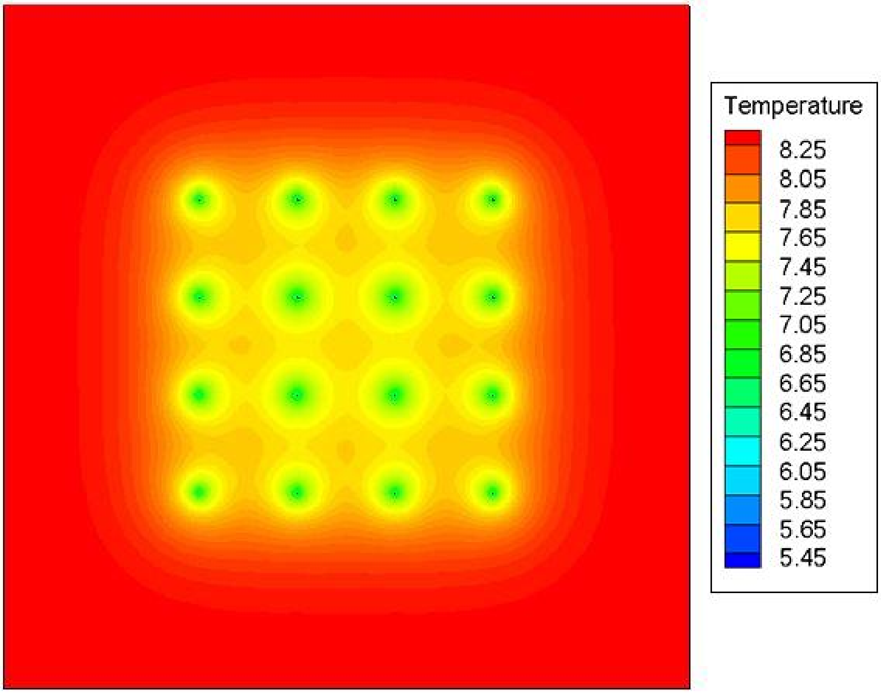


Fig 4-8 The soil temperature change during January 26 to February 25

Fig 4-8 illustrates the soil temperature field observed between January 26 and February 25, following one month of system operation, marking a total operational period of four months. Examining the figure, it becomes apparent that the soil temperature continues to decline, with a range of approximately 0.55°C to 2.8°C.

Notably, the heat exchanger positioned at the center of the tube cluster persistently absorbs heat, causing the surrounding soil temperature to drop to approximately 282.2 K. The mutual interference among the heat exchangers located at the periphery of the tube cluster becomes more evident during this stage. Consequently, a region of the soil with lower temperatures, compared to Figure 4-10, emerges in the middle of the tube bundle. The four heat exchangers within this region experience more significant thermal disturbances originating from both internal interactions, such as between adjacent heat exchangers, as well as external influences from the surrounding heat exchangers.

These findings highlight the ongoing progression of the system over four months of operation, revealing a continued decrease in soil temperature and the amplification of thermal interactions among the heat exchangers. The formation of a region with lower soil temperatures in the middle of the tube bundle emphasizes the complexity of the thermal dynamics and the need for careful consideration of thermal disturbances in optimizing the system's performance and ensuring its long-term stability.

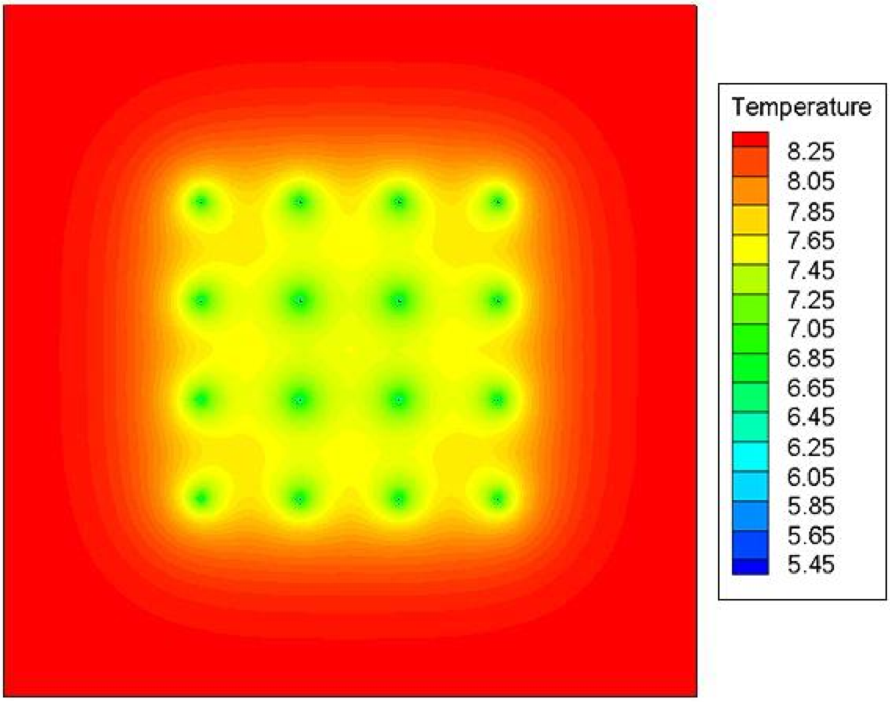


Fig 4-9 The soil temperature change during February 26 to March 25

Fig 4-9 depicts the soil temperature field observed between February 26 and March 25, after one month of system operation, indicating a cumulative operational period of five months. Analysis of Fig 4-9 reveals a persistent decline in soil temperature, ranging from approximately 0.75°C to 3.0°C.

Significantly, the mutual interference among the four heat exchangers situated at the center of the well cluster and the eight heat exchangers at the periphery intensifies during this stage. This heightened interaction between heat exchangers results in the formation of a substantial area characterized by a low soil temperature zone within the middle of the tube cluster. This phenomenon, known as a cold buildup, manifests as a region of significantly reduced soil temperature in the soil temperature field.

These observations underscore the progressing thermal dynamics within the system after five months of continuous operation. The persistent decline in soil temperature and the intensified mutual interference between heat exchangers emphasize the complex thermal interactions taking place. The emergence of a distinct area with low soil temperatures further emphasizes the importance of managing thermal imbalances and optimizing heat transfer efficiency within the system. Such considerations are essential for maintaining stable system performance and maximizing the overall effectiveness of the ground-source heat pump technology.

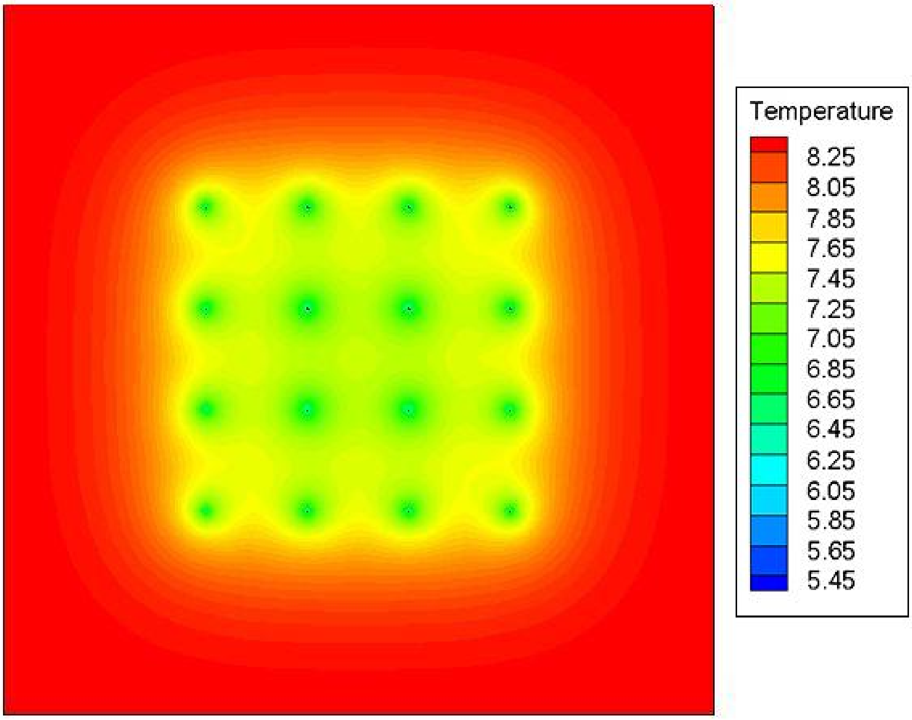


Fig. 4-10 The soil temperature change during March 26 to April 15

Fig 4-10 showcases the distribution of the soil temperature field over a span of 20 days, specifically from March 26 to April 15, marking the conclusion of the heating season for the entire system operation. An examination of the figure reveals that, as the system continues to operate, the soil temperature within the well cluster arrangement area experiences a further decrease, ranging from approximately 1.05°C to 3.15°C.

Comparing these results with those presented in Figure 4-6, it becomes evident that the soil's low-temperature zone has expanded to encompass the entire well cluster arrangement area. Furthermore, the phenomenon of cold buildup within the soil temperature field becomes even more pronounced. The cold buildup refers to the intensified formation of a distinct region characterized by significantly lower soil temperatures, representing a further amplification of thermal imbalances within the system.

These observations highlight the continued progression of the thermal dynamics as the system nears the end of its heating season. The persistent decline in soil temperature, coupled with the expanding low-temperature zone and the evident cold buildup phenomenon, emphasizes the importance of effectively managing the thermal imbalances within the system. Strategies for mitigating these imbalances and optimizing the heat transfer efficiency are crucial for ensuring the long-term stability and performance of the ground-source heat pump technology.

Following the conclusion of the heating period, the Evergreen area transitions into the intermediate season. During this transitional phase, the soil surrounding the heat exchange zone undergoes a process of natural heat diffusion. This diffusion allows for the exchange of heat between the soil within the heat exchange zone and the soil outside of it. As a result, the soil temperature gradually achieves a state of balance as the heat is redistributed throughout the surrounding area.

This observation underscores the dynamic nature of soil temperature regulation during different operational phases. The heating condition leads to a steady decrease in soil temperature due to continuous heat extraction, while the subsequent transition period facilitates a more balanced temperature distribution through natural heat diffusion. Understanding and considering these seasonal variations in soil temperature are vital for ensuring the effective and efficient operation of the ground-source heat pump system in the Evergreen area.

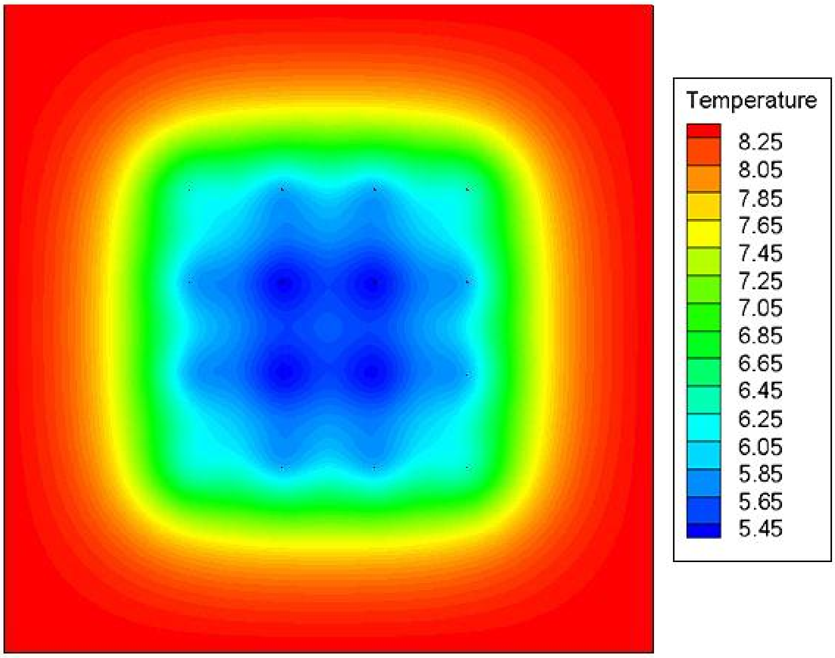


Fig 4-11 The soil temperature change during April 16 to May 31

Fig 4-11 portrays the natural recovery of the soil temperature field during the transition period from April 16 to May 31, marking the progression after 7 months of system operation. Upon observing the figure, it becomes apparent that the thermal interference among the buried heat exchanger tubes has significantly diminished. The temperature within the central region of the tube cluster exhibits an increase of 2.01°C compared to the temperature field observed at the conclusion of the heating season. However, it still registers a decrease of 1.14°C when compared to the initial soil temperature.

These observations lead to the conclusion that the soil temperature has undergone a process of recovery through natural means, gradually returning to its equilibrium state after the heating season. Although the soil temperature demonstrates signs of recovery compared to the end of the heating season, there persists a cold accumulation within the soil temperature field when compared to the initial soil temperature. This implies that the soil temperature field retains residual effects from the initial period of cold buildup, indicating the importance of managing the long-term thermal imbalances within the system.

Understanding the behavior of the soil temperature field during the transition period is crucial for optimizing the operational stability and efficiency of the ground-source heat pump system. By considering these natural recovery processes, appropriate measures can be implemented to mitigate the long-term impacts of thermal imbalances and ensure the sustainable performance of the system.

The heat pump unitsinitiated operation in summer starting from June 1 and ceased operation at the end of August. During this period, the heat pump system facilitated the cooling of the building and transferred heat to the soil. As a result, the soil temperature gradually increased, offering some relief from the phenomenon of cold accumulation that occurs under heating conditions.

Understanding the soil temperature dynamics during the transition period and the subsequent cooling phase is vital for optimizing the performance of the ground-source heat pump system. By comprehending these natural recovery processes and the influence of cooling operations, strategies can be devised to effectively manage the thermal imbalances and ensure the system operates in a stable and efficient manner.

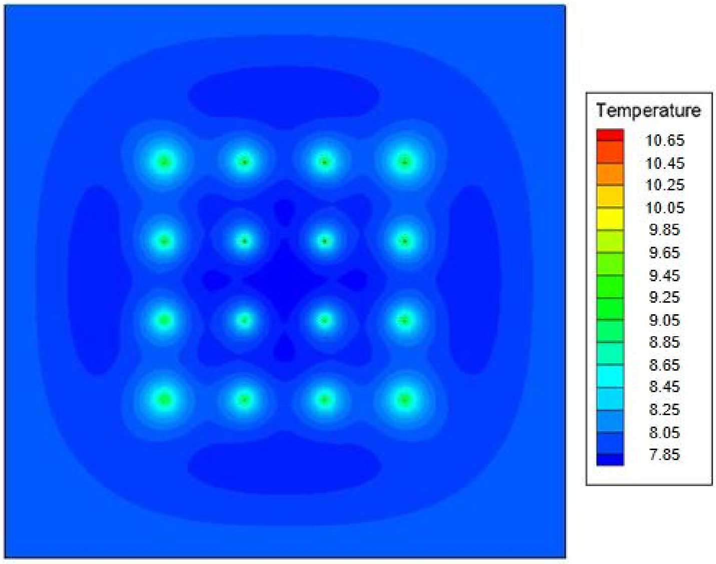


Fig 4-12 The soil temperature change during June 1 to June 30

Fig 4-12 provides a visual representation of the soil temperature distribution in the heat pump system after one month of operation under cooling conditions, specifically from June 1 to June 30. This corresponds to the eighth month of system operation, enabling us to observe changes in the soil temperature field surrounding the well cluster. Analyzing Fig 4-14, it is evident that the soil temperature around the soil heat exchanger experienced a rapid increase, reaching a value of 287.4 K. This temperature was 2.4°C higher than the initial soil temperature. At the periphery of the well cluster, the soil temperature recovered more swiftly, ultimately reaching the same temperature as the initial soil temperature. However, in the center of the well cluster, where cold accumulation occurred, the soil temperature exhibited a slower recovery rate. As a result, it remained between 0.6°C and 0.9°C lower compared to the initial soil temperature.

Understanding these soil temperature dynamics during the cooling phase is crucial for optimizing the performance of the heat pump system. By identifying areas where the soil temperature recovery is slower and acknowledging the effects of cold accumulation, strategies can be devised to enhance the system's efficiency and ensure a balanced thermal distribution within the soil. This knowledge allows for effective management of the system, enabling it to operate at its full potential and deliver optimal cooling performance.

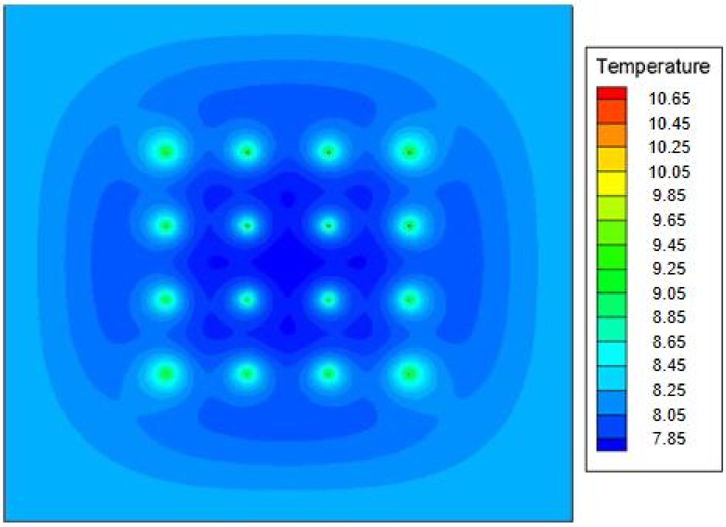


Fig 4-13 The soil temperature change during July 1 to July 31

Fig 4-13 presents a visualization of the soil temperature distribution in the heat pump system during the cooling operation in July. This period marks the ninth month of continuous system operation and provides insights into the changes in the soil temperature field surrounding the well complex.

Upon closer examination of Figure 4-15, it is evident that the soil temperature has increased compared to the previous month. This progress indicates the effectiveness of the recovery process, as the soil temperatures at the periphery of the well cluster have even surpassed the initial values. This demonstrates the restoration of soil temperature equilibrium, which is a key outcome of the cooling operations.

However, it is worth noting that within the core of the well cluster, the soil temperatures still slightly lag behind the initial values. These differences range from 0.3°C to 0.6°C, indicating some variations within the system. Nevertheless, the overall impact of these disparities is relatively minor considering the significant reduction in cold accumulation within the soil temperature field.

These observations have important implications for decision-making. Understanding the dynamic changes in the soil temperature field allows for the development of strategies to optimize the performance of the heat pump system during the cooling phase. With this knowledge, measures can be implemented to improve efficiency and enhance the overall system performance, resulting in increased cooling capacity to meet environmental requirements effectively.

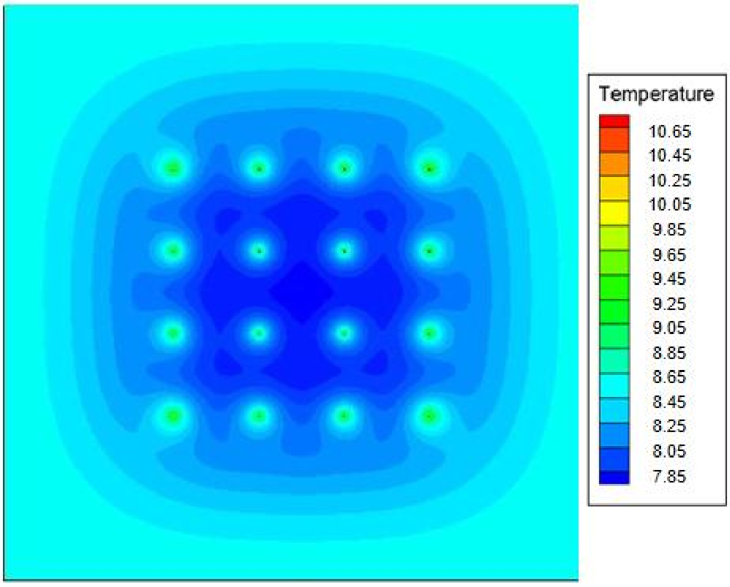


Fig 4-14 The soil temperature change during July 1 to July 31

Fig4-14, a captivating illustration, unravels the intricate soil temperature field distribution of the heat pump system throughout the entire cooling operation undertaken during the month of August, from the 1st to the 31st. This significant interval, marking the system's tenth month of continuous operation, offers an invaluable opportunity to delve into the changes transpiring within the soil temperature field encircling the well complex.

Immersing oneself in the remarkable details unveiled within Fig 4-16, an unmistakable trend emerges—the heat exchanger tirelessly radiates heat to the soil, eliciting a remarkable surge in the soil temperature in its immediate vicinity. Astonishingly, the soil temperature in this region soared to an impressive 288 K, surpassing the initial soil temperature by a noteworthy 3.0°C. This phenomenal rise unequivocally signifies the efficiency and efficacy of the heat transfer process facilitated by the heat pump system.

Furthermore, a subtle yet promising upturn in temperature was discernible within the center of the well cluster, culminating at a notable 284.7°C. Although this value still stands 0.3°C lower than the initial soil temperature, it stands as a testament to the positive recovery trajectory achieved through diligent cooling operations. Notably, the persistent issue of cold accumulation that once plagued the soil temperature field has once again been effectively mitigated, signifying the resounding success of the cooling system's operation.

These noteworthy findings underscore the unwavering efficiency and prowess of the heat pump system in expeditiously dissipating heat to the soil during the cooling phase. By seamlessly managing the intricate process of heat transfer, the system ensures the maintenance of a stable and harmonious distribution of soil temperature. This paramount achievement culminates in optimal system performance and an amplified cooling capacity that diligently meets and surpasses the demands imposed upon it.

This remarkable phenomenon can be attributed to the pivotal role played by the heat exchanger, which tirelessly disseminates heat from the building into the soil. Consequently, the soil retains and accumulates this dispersed heat, resulting in a continuous and gradual rise in temperature. This intricate process ensures the preservation of the soil temperature at the predetermined value specified by the system. Consequently, it facilitates the attainment of optimal performance from the system during subsequent heating conditions.

The significance of this temperature regulation mechanism cannot be overstated. It bestows the system with operational stability and enhances its overall effectiveness. By consistently maintaining the soil temperature within the desired range, the system guarantees a conducive environment for efficient operation, thus minimizing any potential disruptions.

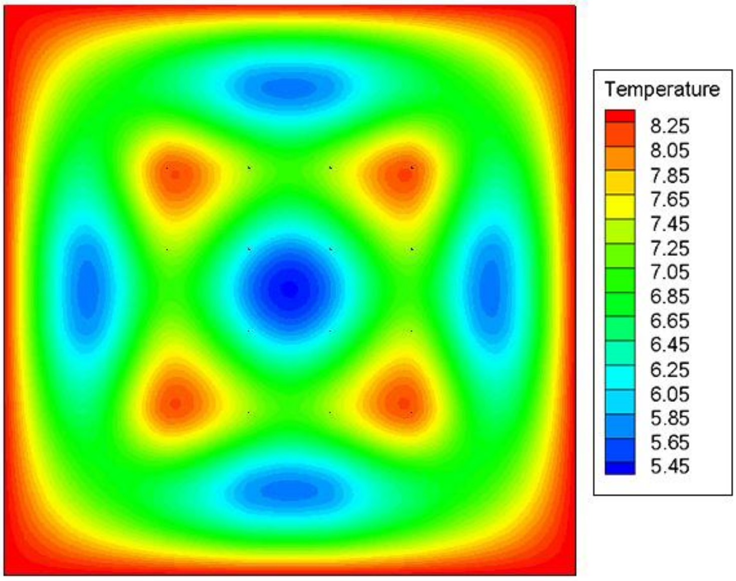


Fig 4-15 The soil temperature change during September 1 to October 24

Fig4-15, offers a profound glimpse into the dynamic changes unfolding within the soil temperature field during the crucial natural recovery phase at the culmination of the cooling period, marking an impressive one year of continuous system operation. This period serves as a pivotal juncture, wherein the intricate interplay between the system and the environment is brought to the forefront, providing invaluable insights into the state of the soil temperature field surrounding the well cluster.

Immersing ourselves in the intricate details portrayed within Fig 4-18, a remarkable phenomenon unravels before our eyes—the temperature field around the heat exchanger exhibits a complete recovery, with the soil temperature triumphantly returning to its initial state. This resounding achievement signifies the effectiveness of the system's natural recovery process, successfully reinstating the soil temperature to its original equilibrium.

However, upon closer examination of the central region of the well cluster, a subtle deviation in temperature manifests itself. Reaching a measured value of 284.85 K, this temperature slightly lags behind the initial soil temperature by a minuscule 0.15°C. While this variance suggests the presence of residual effects from the preceding cooling phase in this specific area, it remains inconsequential when considering the broader picture of system performance.

The overarching success of the natural recovery process is undeniable, as it diligently restores the soil temperature to a steadfast and harmonious state. This accomplishment ensures the creation of optimal conditions, laying the foundation for a subsequent operating cycle marked by efficiency, stability, and enhanced performance. It is through these diligent efforts that the system can consistently meet and surpass the demands imposed upon it, bolstering its overall effectiveness and solidifying its position as a reliable and resilient component of the larger infrastructure.

Delving into the depths of the figures, a discernible pattern emerges—the soil temperature experiences a slight decline at the onset of the transition phase, followed by a period of remarkable stabilization. This intriguing behavior finds its roots in the profound dynamics of heat transfer within the soil. Under the influence of cooling supply conditions, the soil acts as an absorptive agent, diligently storing the heat that permeates its depths.

However, as the cooling supply conditions come to an end, the soil relinquishes its reliance on the heat exchanger as a primary heat storage mechanism. Consequently, a gradual release of the accumulated heat into the surrounding environment ensues, leading to a modest decline in the soil temperature. This remarkable phenomenon unfolds through the intricate process of heat transfer, as the absorbed heat dissipates into the surroundings.

Nevertheless, the soil temperature soon finds equilibrium as the intricate dance between heat dissipation and absorption reaches a harmonious balance. It is within this tranquil state that the establishment of an equilibrium thermal condition within the soil takes shape. This steadfastness and stability serve as a testament to the intricate interplay between the system and its environment, highlighting the system's ability to adapt and transition seamlessly from one phase to another.

The establishment of this equilibrium thermal state within the soil sets the stage for subsequent operations, laying a solid foundation for optimal performance and efficiency. By harnessing the inherent equilibrium achieved during this natural recovery phase, the system stands poised to embark on future cycles with enhanced effectiveness and resolute stability, ensuring its ability to meet the demands of its operational context with unwavering excellence.

Analyzing the overall changes in the soil temperature field over the year, several observations can be made. During the heating condition and transition season, the heat exchanger consistently extracts heat from the soil, leading to incomplete replenishment of heat in the soil. This results in the formation of a cold accumulation layer in the middle section of the heat exchanger area. Conversely, during cooling conditions and the transition season, the heat exchanger releases heat to the soil, enabling the soil around the heat exchanger to absorb a portion of the heat and restore the soil temperature to its initial level.

Through the year-round operation of the heat pump system, the soil temperature around the pipe cluster exhibits a slight decrease of 0.15°C compared to the initial soil temperature. Ultimately, the soil temperature field reaches a state of equilibrium. These findings serve as initial evidence that the adopted heat compensation method, involving zone division control, is feasible in cold regions.

4.4.2 System long-term operation simulation results and analysis

In the study of a soil heat pump system, the soil temperature field undergoes continuous changes throughout its operation. As discussed in section 4.6.1, an analysis was conducted to simulate the system's performance after one year of operation, revealing a relatively balanced soil temperature field. However, to truly assess the economic and environmental benefits of the soil source heat pump system, it is necessary to examine its long-term stability. Thus, this section aims to simulate the system's operation over a period of 30 years, specifically focusing on the soil temperature conditions after three decades of continuous operation. This extended simulation aims to further validate the feasibility of the thermal compensation method employed for the control zone of the heat pump system in this project. By assessing the soil temperature dynamics over an extended timeframe, a more comprehensive understanding of the system's long-term performance and its ability to maintain a stable thermal environment can be obtained.

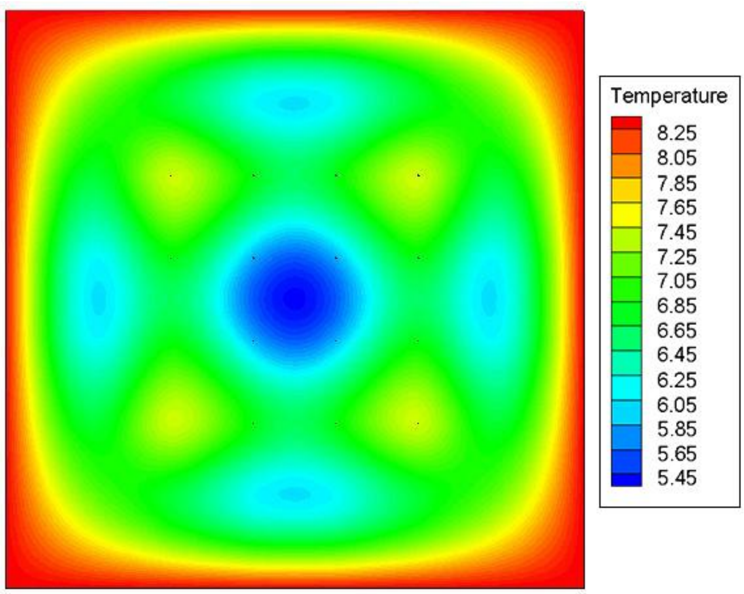


Fig 4-16 The soil temperature change during 2 years

Fig 4-16 provides an insightful glimpse into the evolution of the soil temperature field after 2 years of continuous operation of the system. A comparative analysis with the soil temperature field after one year reveals notable changes. Notably, the cold accumulation zone in the center of the well cluster has expanded further, with the soil temperature in the central region reaching 284.75 K. This represents a decrease of 0.1°C compared to the soil temperature observed in the first year of operation and a reduction of 0.25°C when compared to the initial soil temperature. These findings suggest a gradual increase in the extent of the cold accumulation phenomenon within the system's thermal environment, reinforcing the need for effective strategies to manage and mitigate thermal imbalances over the long term.

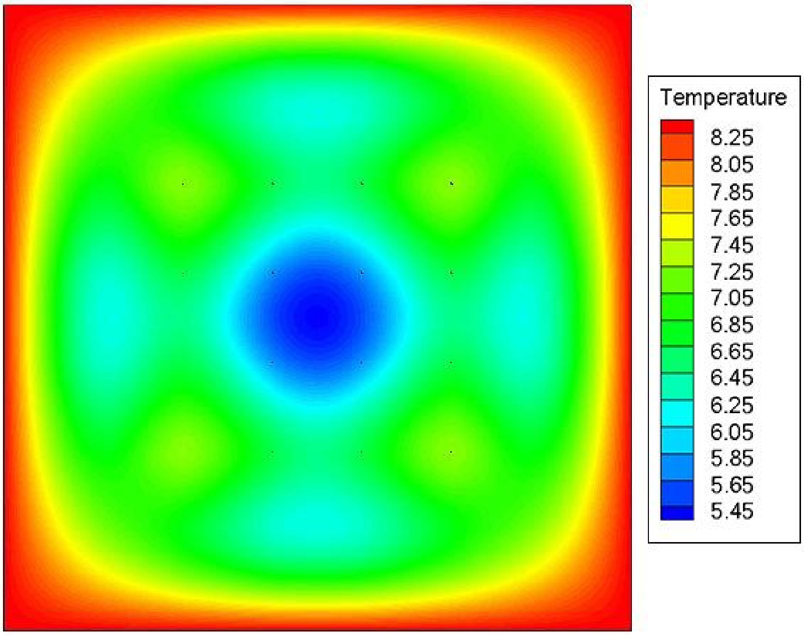


Fig 4-17 The soil temperature change during 3 years

Figure 4-17, shows the profound changes in the soil temperature field that occurred after 3 years of uninterrupted operation of the system. The soil temperature fields used to compare and contrast the observations after the first year reveal a large number of important trends that deserve closer examination. Upon closer examination of the soil temperature field, several key observations come to the fore. One trend is the further expansion of the cold accumulation zone in the center of the well cluster. This expansion had a tangible impact, resulting in a significant drop in soil temperature in the central area, plummeting to a measured value of 284.68 K. This large drop reflects a significant decrease of 0.17°C compared to the soil temperature recorded in the first year and even a significant drop of 0.32°C compared to the initial soil temperature.

These findings not only highlight the persistence of cold accumulation within the system, but also mark a remarkable state of relative equilibrium and successful recovery within the soil temperature domain. It is critical, however, to recognize the significance of these results, which reinforce the critical need for ongoing monitoring and implementation of robust management strategies. These measures are essential to ensure the long-term stability and continued optimal performance of soil source heat pump systems.

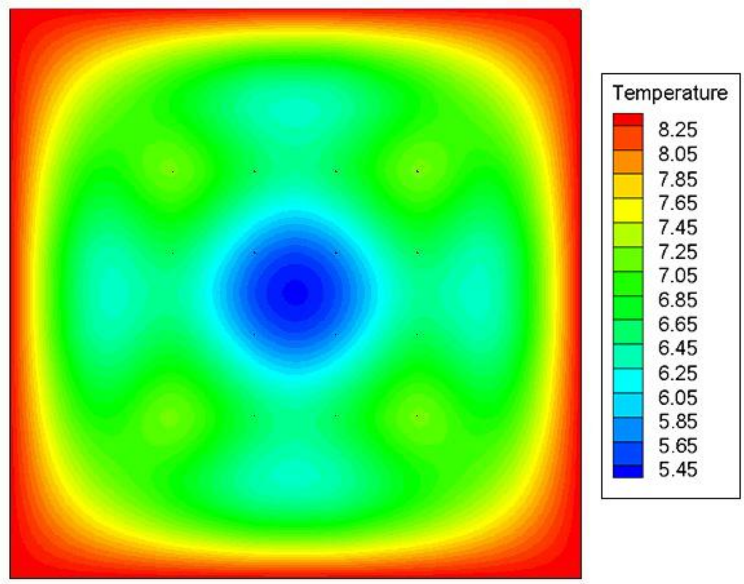


Fig 4-18 The soil temperature change during 5 years

Fig 4-18 illustrates the changes in the soil temperature field after 5 years of continuous operation of the system. A closer look at the details in the figure reveals a clear trend comparing the changes in the soil temperature field observed in the first year with the current one. In the central area of the well cluster, the soil temperature decreases slightly, reaching a measured value of 284.64 K. Compared to the soil temperature recorded in the first year, this drop was 0.21°C, a decrease of 0.36°C relative to the initial soil temperature.

These findings indicate the persistence of cold accumulation after four years of system operation, resulting in a gradual decrease in soil temperature. Although these changes may be relatively small, their significance cannot be underestimated.

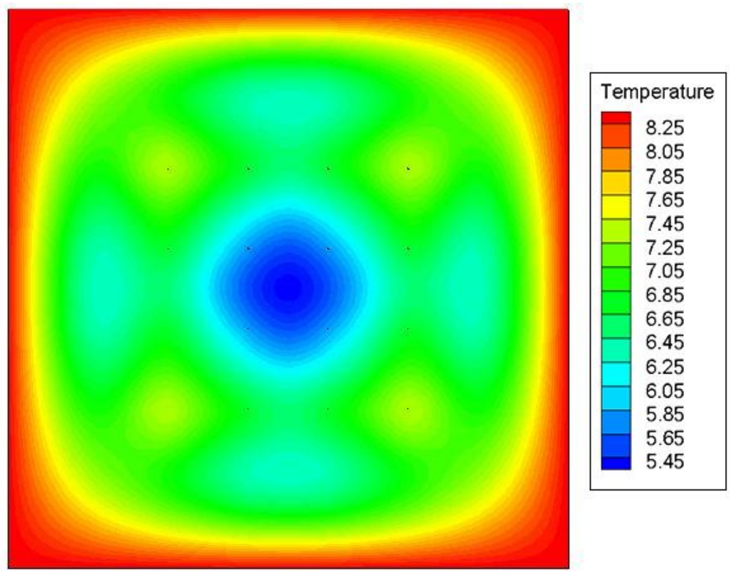


Fig 4-19 The soil temperature change during 8 years

Fig 4-19 visually presents the evolution of the soil temperature field after the system has been operational for a span of 8years. A detailed analysis of the figure reveals intriguing insights when comparing the changes in the soil temperature field to those observed after the initial year. Notably, there is a marginal decline in the soil temperature at the center of the well cluster, reaching a value of 284.59 K. This modest decrease of 0.26°C, compared to the soil temperature recorded in the first year, signifies a significant drop of 0.41°C relative to the initial soil temperature. The remarkable aspect is the overall balance achieved in the soil temperature field, with the soil temperature exhibiting substantial recovery.

These findings underscore the efficacy of the soil source heat pump system over its operational lifespan, as it gradually mitigates cold accumulation and works towards maintaining stable soil temperature conditions. It is evident that the system's long-term performance relies on the continued implementation of effective control and management strategies to ensure its sustained success in providing efficient and environmentally friendly heating and cooling solutions.

4.4.3 Variation of soil temperature for long-term operation with different pipe spacing

Fig4-20 to 4-22 provide visual illustrations of the temperature distribution within a 100-meter soil layer following the completion of the 30th heating cycle in the simulation. These figures focus on three distinct configurations of heat exchange borehole groups with different spacing: 4 meters, 5 meters, and 6 meters. Through a comprehensive analysis of these figures, several fascinating insights emerge, shedding light on the connection between heat exchange hole spacing and the dynamics of soil temperature.

One striking observation emerges from comparing the soil temperature drops among the different spacing configurations. The 4-meter spacing heat exchange borehole group exhibits a remarkable temperature drop of 26.82%, followed closely by the 5-meter spacing group with a drop of 24.39%, and finally the 6-meter spacing group with a relatively lower drop of 21.95%. This trend highlights a crucial correlation: as the spacing between heat exchange holes increases, the rate of soil temperature decrease diminishes accordingly. These results underscore the intricate interplay between heat exchange hole spacing and its impact on the thermal dynamics within the soil. In addition to the variation in soil temperature drops, another significant finding emerges from analyzing the distribution of the soil temperature field among the three well groups. Notably, a remarkable similarity is observed, emphasizing a consistent pattern of thermal disturbance within the central regions of each well group. This discovery underscores the pivotal role played by the central region in shaping the overall thermal performance of the soil heat pump system. It emphasizes the importance of carefully managing and optimizing the heat exchange dynamics within this central zone to ensure optimal system efficiency and performance.

Further analysis, focusing on the comparison of soil temperature around each heat exchanger borehole with the initial soil temperature, reveals an encouraging result: a significant decrease in soil temperature across all spacing configurations. Interestingly, no significant difference is observed in the rate of soil temperature decline between the 4-meter, 5-meter, and 6-meter spacing configurations. This finding aligns harmoniously with conclusions drawn from actual projects, further validating the feasibility and viability of utilizing a 4-meter heat exchanger hole spacing in practical applications.

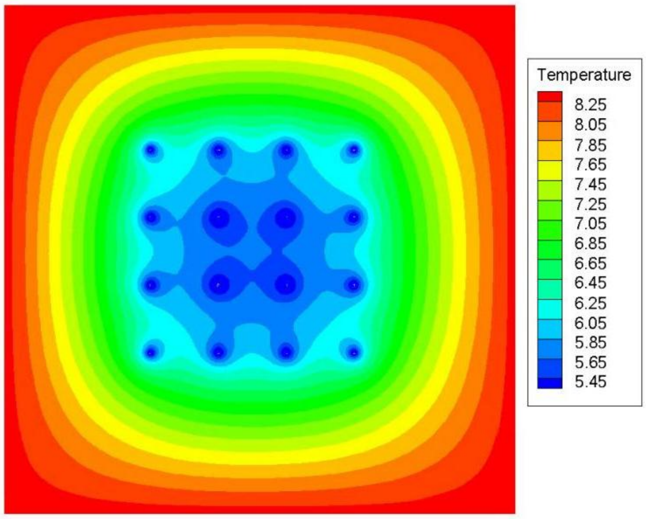


Fig 4-20 The soil temperature field after 30 years of operation was simulated with heat exchanger holes with a distance of 4m

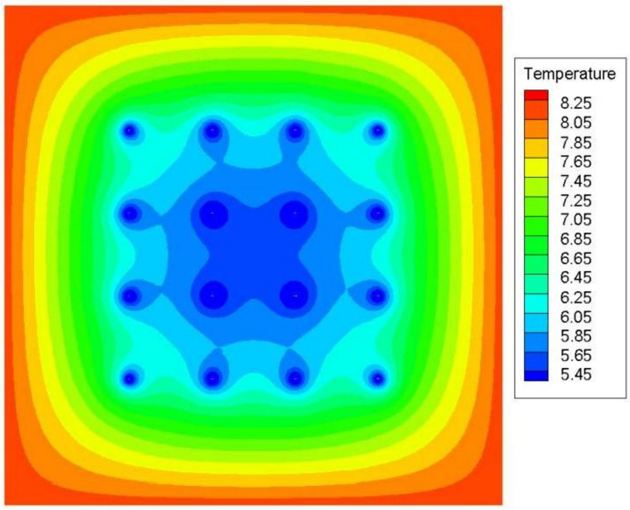


Fig 4-21 The soil temperature field after 30 years of operation was simulated with heat exchanger holes with a distance of 5m

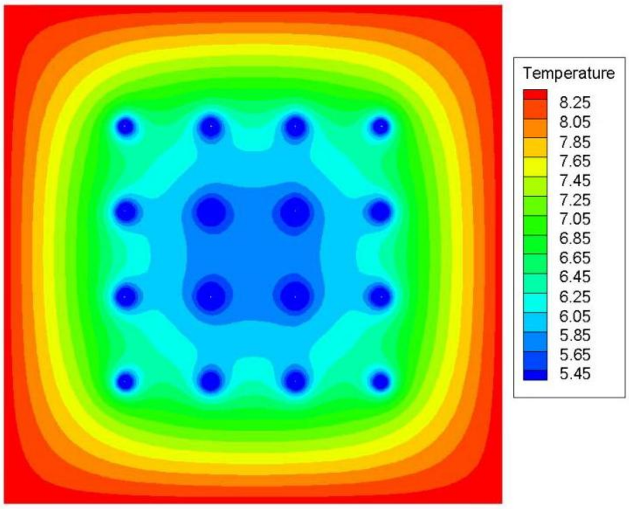


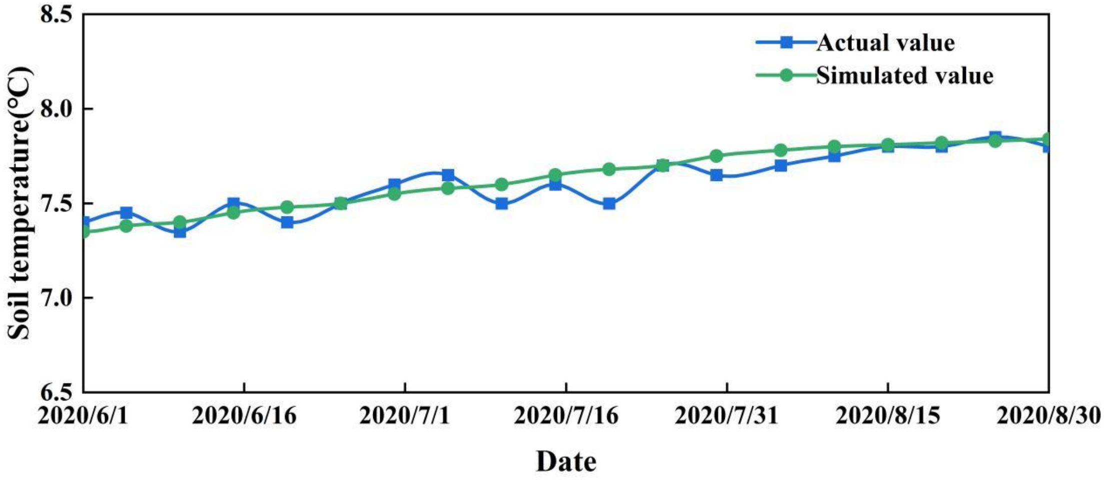
Fig 4-22 The soil temperature field after 30 years of operation was simulated with heat exchanger holes with a distance of 6m

4.4.4 Verification of simulation results

To ensure the validity of the simulation results, an analysis was conducted using Fig 4-28, which revealed that the soil temperature at a depth of 40 meters exhibited greater variation. Hence, the simulated data at this depth were selected for further examination. Specifically, the focus was on a well set featuring a heat exchange hole spacing of 4 meters and a soil depth of 40 meters. A comparison was made between the measured and simulated data during both the cooling conditions from June to August 2020 and the heating conditions from November 2020 to January 2021, as depicted in Fig 4-23.

Impressively, the monitoring data aligned closely with the simulated data, exhibiting maximum errors of only 2.3% and 2.1%, respectively. The soil temperature variation curve during the cooling period exhibited a consistent upward trend, while the curve during the heating period displayed a consistent downward trend. In contrast, the simulated data curves of soil temperature changes remained relatively stable and exhibited minimal fluctuations when compared to the measured data. It is worth noting that these simulations represent an ideal scenario and do not account for various complex influencing factors, such as the precision of monitoring equipment, water and seepage dynamics within the soil, and outdoor temperature fluctuations.

The convergence between the simulated and measured data within acceptable error margins confirms the reliability and accuracy of the simulation model. While acknowledging the limitations of the simulation, this analysis provides valuable insights into the general trends and patterns of soil temperature variations under different operating conditions. These findings contribute to the overall understanding of soil heat pump systems and lay a solid foundation for optimizing their design and performance in practical applications.



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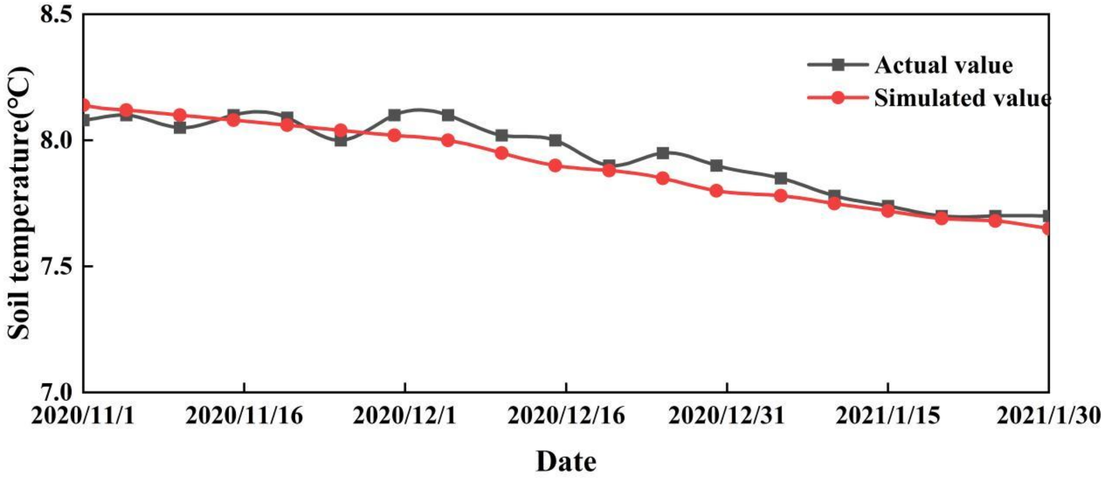

b

Fig 4-23. Comparison of actual value and simulated value under cooling condition and heating condition

4.5 Optimization scheme of heat exchange hole spacing

Fig 4-31 to 4-33 provide valuable insights into the impact of different well group spacing on the soil temperature field. These figures demonstrate that the soil temperature surrounding the heat exchange borehole group decreases to varying degrees. Specifically, the 4-meter spacing well group affects an area of 729 square meters of soil temperature change, while the 5-meter spacing well group influences 841 square meters, and the 6-meter spacing well group covers an area of 1089 square meters of soil temperature change. This is due to the fact that when the ground-source heat pump system was under operation, the ground-source heat exchanger in the borehole exchanged heat with the soil, absorbing heat for heating or releasing heat for cooling. This will have an effect on the surrounding soil temperature. In the heating mode, the ground-source heat pump system will absorb heat from the soil, causing a slight decrease in the soil temperature around the borehole. In the cooling mode, the system will release heat into the soil, resulting in a slight increase in soil temperature around the borehole. The effect of the borehole on the surrounding soil temperature existed within a certain range; however, the disturbance radius of the borehole increased as the borehole spacing increased, and the extent of the alignment and footprint on the horizontal plane expanded, resulting in a wider range of soil temperature variation.

It is evident that the 4-meter spacing well group, although more land-efficient, has a comparatively smaller impact on the thermal stability of the surrounding soil temperature field when compared to the 5-meter and 6-meter spacing heat exchange borehole groups. This finding highlights the importance of reducing the area occupied by heat exchange borehole sets in ground-source heat pump (GSHP) projects in cold regions to ensure the thermal stability of the surrounding soil temperature field and the overall ecosystem.

In this particular project, a total of 120 heat exchanger holes were set up following a 12x10 arrangement. When considering the minimum floor area required for each spacing, the 4-meter borehole spacing occupies 1584 square meters, the 5-meter spacing requires 2475 square meters, and the 6-meter spacing necessitates 3564 square meters. Notably, the use of 4-meter hole spacing saves 891 square meters and 1980 square meters of land area compared to the 5-meter and 6-meter spacing, respectively. This reduction in land area corresponds to a decrease of 36% and 55.5% in the minimum floor area, signifying significant cost savings in terms of construction and project area.

The adoption of 4-meter hole spacing not only optimizes land usage but also contributes to the overall efficiency and cost-effectiveness of the GSHP project. By carefully considering the spacing of heat exchange boreholes, engineers and designers can strike a balance between achieving thermal stability and minimizing the environmental impact of the system.

4.6 Summary

This chapter presents empirical data and simulation studies that validate the effectiveness of ground source heat pump (GSHP) systems in addressing soil thermal imbalances and ensuring long-term stability.

First, after 8 years of continuous operation, the maximum temperature difference in soil temperature ranged from 0.13°C to 0.51°C. This demonstrates the successful implementation of zone technology in mitigating soil thermal imbalance and extending system life.

Secondly, the simulation results show that the soil temperature around the pipe set is 0.15°C lower than the initial soil temperature through the year-round operation of the heat pump system, and the soil temperature field basically reaches the equilibrium state, which initially proves that the thermal compensation method with controlled zone division adopted in this project is feasible in cold regions.

Finally, the results of the simulated operation for 30 years show that the soil temperature around the buried pipes slightly decreases, indicating that the impact on the overall soil temperature field is small, which further supports the assertion that the ground source heat pump system effectively solves the soil thermal imbalance. The decrease in soil temperature was 26.82% for the 4-meter spacing heat exchange hole group, 24.39% for the 5-meter spacing heat exchange hole group, and 21.95% for the 6-meter spacing heat exchange hole group. Compared with the initial soil temperature, the soil temperature around each heat exchanger hole also decreased, among which there was no difference in the soil temperature decrease rate between 4 m, 5 m and 6 m. This is also consistent with the conclusion obtained in the actual project, which further verifies the feasibility of 4 m heat exchanger hole spacing applied to the actual project.

The results show that the ground source heat pump system maintains the thermal balance of the subsurface soil temperature by regulating the equalization of the cooling and heating loads in the severe cold region. The practicality of ground source heat pump in severe cold regions is further confirmed by simulation and experimental studies. Meanwhile, by analyzing the changes of soil temperature around the buried tube heat exchange well set with different heat exchange hole spacing, it is found that the difference of each spacing is small after long-term operation, so when the area of ground source heat pump project is limited, it is not necessary to pursue excessively to increase the heat exchange hole spacing to maintain the thermal balance of soil temperature field. If the heat exchange hole spacing is 4 meters, it can still operate stably and efficiently by balancing the hot and cold loads through appropriate methods. In cities with high population density in cold areas, a large amount of land area can be saved by using soil source heat pump systems with a 4-meter spacing to arrange heat exchange borehole sets. The reduction in project cost facilitates the use of GSHPs in cold regions.

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Chapter 5

ENERGY EFFICIENCY ANALYSIS OF GSHPs

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5.1 Content

The common methods for thermodynamic analysis of energy-using equipment or systems are the energy analysis method and the wiring analysis method, collectively referred to as the energy analysis method.

Energy analysis method. It is the most widely used energy analysis method, mainly based on the first law of thermodynamics. The energy analysis method can systematically analyze the energy efficiency of the entire thermal device, and is currently used most often in practical engineering. However, the energy analysis method only analyzes the energy from the perspective of quantitative relationship, but not from the perspective of the quality of energy, and the calculation method is too simple. For the soil source heat pump system, the main evaluation index of the energy analysis method is the performance coefficient of the system, etc.

Exergy efficiency analysis method. Mainly based on the first law of thermodynamics and the second law of thermodynamics as the theoretical basis. The method of analysis of assembly effectively combines energy analysis (quantitative) and entropy analysis (qualitative), avoids the one-sidedness of either method, performs a deeper analysis, is comprehensive and scientific, reflects the process of gradual degradation of energy quality, and is more accurate in its calculation.

In the energy conservation analysis, since the energy utilization of each component in the system cannot be reflected when the system is simply analyzed for energy efficiency, this chapter will analyze the basement of this demonstration project system on the basis of energy conservation analysis to reflect the nature of energy transformation and transfer in the system in the process of transmission and put forward optimization suggestions.

5.2 Introduction

Ground Source Heat Pumps (GSHPs) has received a lot of attention in cold regions as a sustainable and efficient heating solution[1-3]. GSHPs provide heating by transferring heat from outdoors to indoors and cooling by extracting heat from a hotter space to a cooler space[4, 5]. Compared to conventional cooling and heating systems, GSHPs offer several advantages in terms of technical efficiency, economic viability, and environmental sustainability[6-8]. They are highly efficient in utilizing renewable energy sources, resulting in energy savings and reduced operating costs[9-12]. Understanding the energy use efficiency and energy loss of GSHP systems can help us to evaluate their performance and identify potential room for improvement[13]. In cold regions, where energy consumption and heating loads are high, optimizing the energy performance of GSHPs is important to provide sustainable heating solutions.

Through energy analysis, we can determine the energy use efficiency of GSHPs. [14] conducted a comparative experiment to compare the efficiency of GSHPs and air source heat pump systems (ASHPs) after 1 year of operation. The results showed that the GSHPs outperformed the ASHPs in terms of energy consumption savings. Specifically, the GSHPs saved 43.17% of primary energy consumption in heating conditions and 37.18% in cooling conditions compared to the ASHPs. [15] found that in winter the coefficient of performance (COP) values of

GSHP were found to be higher than the COP values of air source heat pumps. The operation of the compressors is quite stable. Since hermetic compressors show a lower risk of failure, they are quite suitable for long-term operation. [16] conducted a study on the performance of GSHP after 5 years of operation and found that the system had been operating stably for 5 years with high energy efficiency and no significant impact on the soil thermal environment. These findings underscore the superior energy efficiency of GSHP systems, making them a more efficient and sustainable choice for heating and cooling applications[6, 17]. Understanding how much of the input energy the system is able to convert into an effective heating output[18-20]. This helps us to understand the energy consumption of the system and to assess whether it is performing as expected.

Exergy analysis can help us identify sources of energy loss present in a GSHP system[21, 22], such as incomplete efficiency of system components, heat loss from duct transmission, etc.[23, 24]. [25] analyzed different components of ground source heat pumps (GSHP) based on the concept of exergy. The study showed that the thermal efficiency of the circulating component was 28.6%, while the other components, including the fan, condenser, expansion valve, evaporator, heat exchanger, and compressor, had thermal efficiencies of 64%, 60%, 55%, 53%, 42%, and 38%, respectively. In addition, a comparison of the energy and external energy efficiency of these components showed that the fan showed the greatest difference, highlighting the need to improve its performance. [26] A comprehensive exergy analysis of the GSHP revealed that the location of the largest energy loss ratio in the system is the compressor, the system has greater heat loss in the heating condition than in the cooling condition, and the energy efficiency of the system is significantly lower than that of its components. Therefore, more attention should be paid to the comprehensive exergy analysis of GSHP. These findings underscore the importance of optimizing the individual components of a GSHP system to improve overall energy efficiency[27-29]. By identifying and addressing these potential energy loss issues, we can improve the energy utilization efficiency of the system and reduce energy waste[30-33].

Based on the results of the energy and exergy analysis, we can make recommendations for optimization of GSHPs. These recommendations may include aspects such as improving the efficiency of components and optimizing the configuration and control strategy of the system to further improve the energy performance and overall efficiency of the system in order to reduce energy consumption and environmental impact and provide a sustainable heating solution for cold regions.

5.3 Results and analysis of performance monitoring data

In order to verify the simulation results, the long-term operation data of the ground source heat pump monitoring system were calculated and analyzed. This study selects the data of the system from October 2013 to April 2021, which has been running for 8 years.

5.3.1 Performance coefficient calculation

The research shows that the key factors affecting the energy efficiency of GSHP are unit performance coefficient COP and system performance coefficient COPsys[34]. The performance coefficient of the heat pump unit is calculated according to Equation (5-1) and (5-2), and the system performance coefficient is calculated according to Equation (5-3).

$$COP = \frac{Q}{N_i} \quad (5\text{-}1)$$

$$Q = \frac{VC\rho\Delta t}{3600} \quad (5\text{-}2)$$

$$COP_{sys} = \frac{Q_s}{p} \quad (5\text{-}3)$$

Where: Q is Average heat production (cooling capacity) of unit, kw; Ni is unit average input power, kw; V is user side average flow, m3/h; ρ is average density, kg/m3; C is specific heat capacity at constant pressure, kJ/(kg•℃); Δt is temperature difference between supply and return water at user side, ℃.Qs is Total heat production (cooling capacity) of the heat pump system, kw•h; P is Total power consumed by the system, kw•h

5.3.2 Analysis of monitoring results

During the period from winter 2013 to summer 2021, extensive monitoring of the soil-source heat pump system provided valuable data for analysis. Fig 5-1 and Fig 5-2 present the temperature fluctuations of the ground source water supply and return water under various winter and summer operating conditions. Under winter operating conditions, the average temperature difference between the ground source water supply and return was determined to be 1.52°C. Additionally, the average temperature difference between the supply and return water on the customer side was measured to be 2.58°C.

For summer conditions, the average temperature difference on the ground source side of the system was found to be 2.26°C, while the average temperature difference between the supply and return water on the customer side was 2.02°C.

A thorough analysis of the compiled monitoring data for the winter supply and return water temperatures on the ground source side revealed no significant upward or downward trend. These findings provide strong evidence of the system's stable operation, both on the ground source side and the customer side, throughout the entire monitoring period.

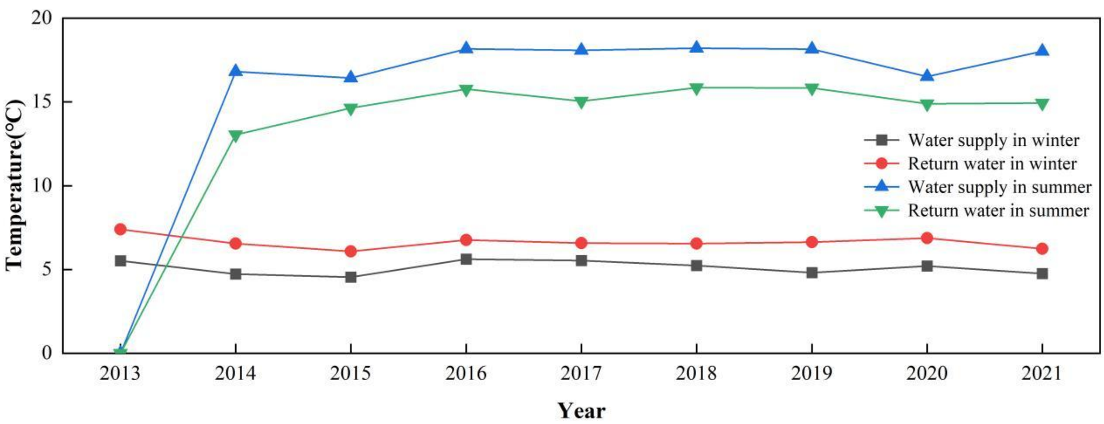


Fig 5-1 Average water supply and return temperature of source side in winter and summer

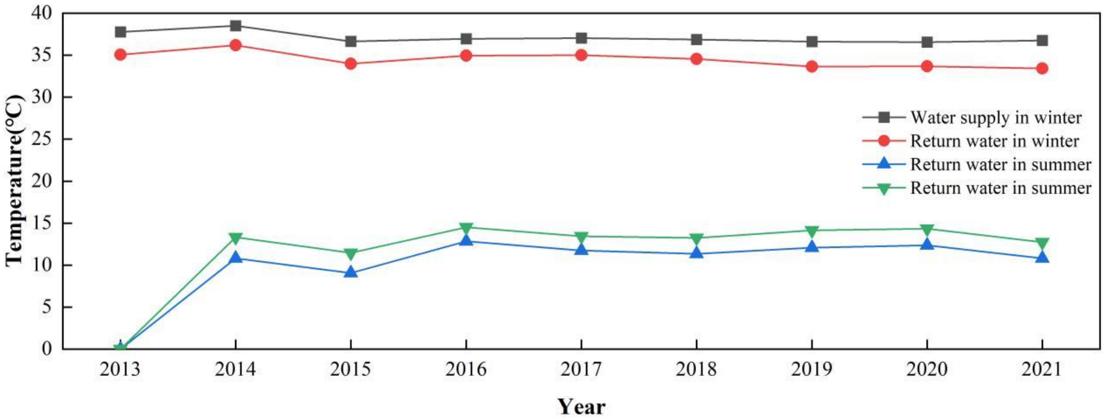


Fig 5-2 Average water supply and return temperature of user side in winter and summer

The data obtained from flow tests conducted through the monitoring system were compiled and analyzed. The average flow rates for both the user side and the ground source side of the heat pump system are presented in Fig 5-3. In winter conditions, the average flow rate on the ground source side was found to be 49.06 m3/h, while on the user side it was 55.21 m3/h. In summer conditions, the average flow rate on the ground source side was 44.13 m3/h. These results indicate a small overall variation in flow rates, demonstrating the system's stable operation.

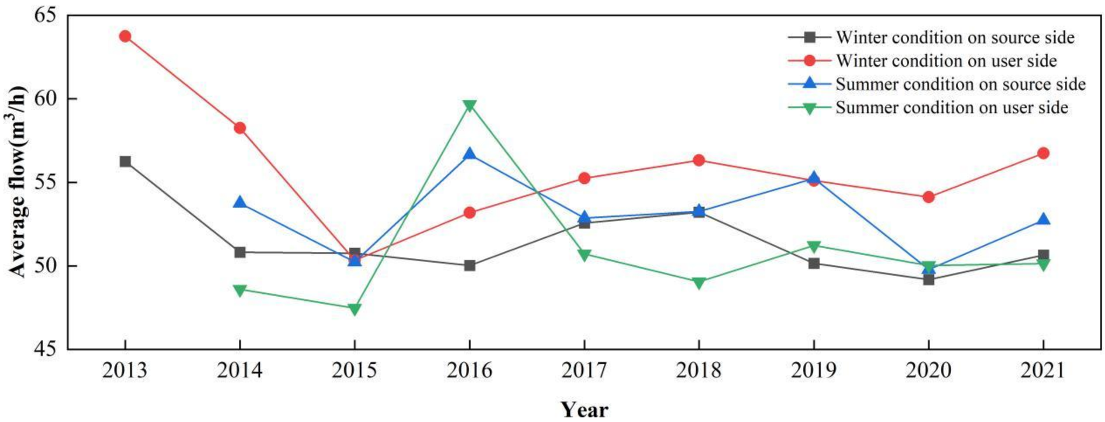


Fig 5-3 Average flow on source side and user side in winter and summer

Fig 5-4 illustrates the variation in the average input power of the heat pump unit. Under winter working conditions, the unit's average input power is measured at 45.18 kW. In summer working conditions, the average input power decreases to 35.81 kW. Throughout the years, both in winter and summer working conditions, the average input power of the unit remains below the rated value, indicating a reasonable selection and design of the unit, as well as a stable operating condition.

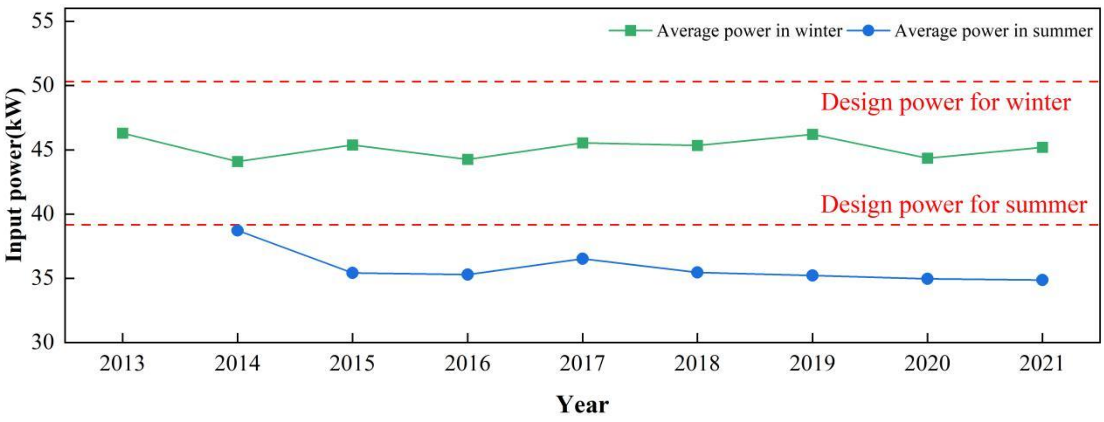


Fig 5-4 Average input power of heat pump unit in winter and summer

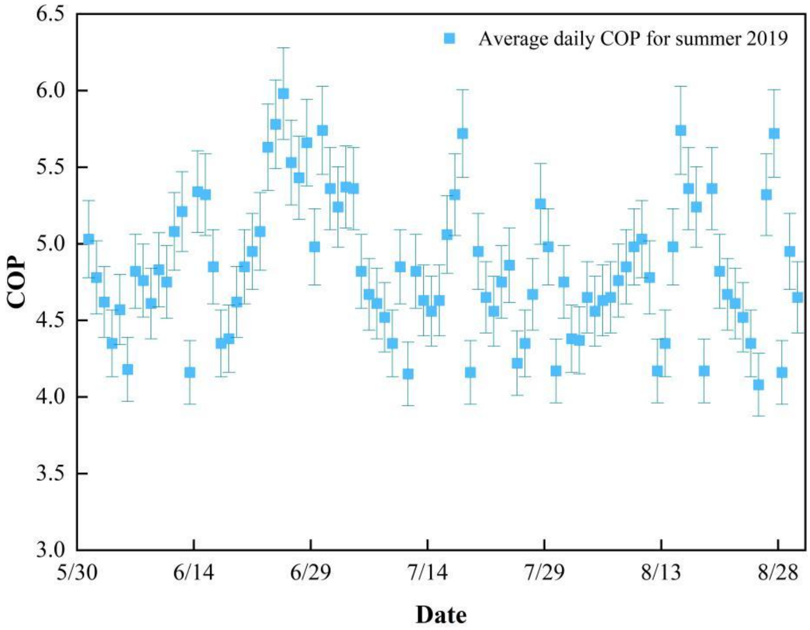
The monitoring system collected data from two cooling cycles and two heating cycles between 2019 and 2020, providing valuable insights into the performance of the unit and the system. The coefficient of performance (COP) for both cooling and heating conditions was calculated and depicted in Fig 5-5 and Fig 5-6, respectively. Analysis of these figures reveals a consistent pattern in the change curves of COP and COPsys for both heating and cooling, indicating the stable operation of the system, in Fig 5-8 and Fig 5-9.

Furthermore, As shown in Figure 5-7, the energy efficiency ratio of the project surpassed the standard energy efficiency requirements in both winter and summer. This signifies the system's positive impact on energy conservation. With an energy efficiency ratio higher than the specified standard, the system exhibits commendable energy-saving performance.

The higher average COP for the unit in summer compared to winter can be attributed to the more favorable operating conditions provided by the low-temperature environment of the underground soil during the summer season. The continuous decrease in water supply temperature on the ground-source side during long-term operation requires more energy to achieve the desired water supply temperature, influencing the COP of the unit.

According to the Chinese national standard GB50189-2005, the COP of heat pump units should not fall below 4.2. Additionally, the Evaluation Standard for Renewable Energy Building Application Projects stipulates a standard energy efficiency ratio of 2.20 for winter systems and 2.70 for summer systems for buried pipe ground source heat pump systems.

After eight years of continuous operation, the system demonstrated impressive performance. The COP compliance rate in winter conditions reached 89.33% compared to the rated COP of 4.2, while in summer conditions, it reached 94.98%. Moreover, the compliance rate of COPsys was 96.88% in winter conditions compared to the rated SPF value of 2.2, and 97.91% in summer conditions compared to the rated COPsys value of 2.7, indicating the system's stable long-term operation and its significant energy-saving benefits. These results affirm the system's adoption of thermal compensation technology, which enables efficient and prolonged operation, contributing to the extended service life of the system.



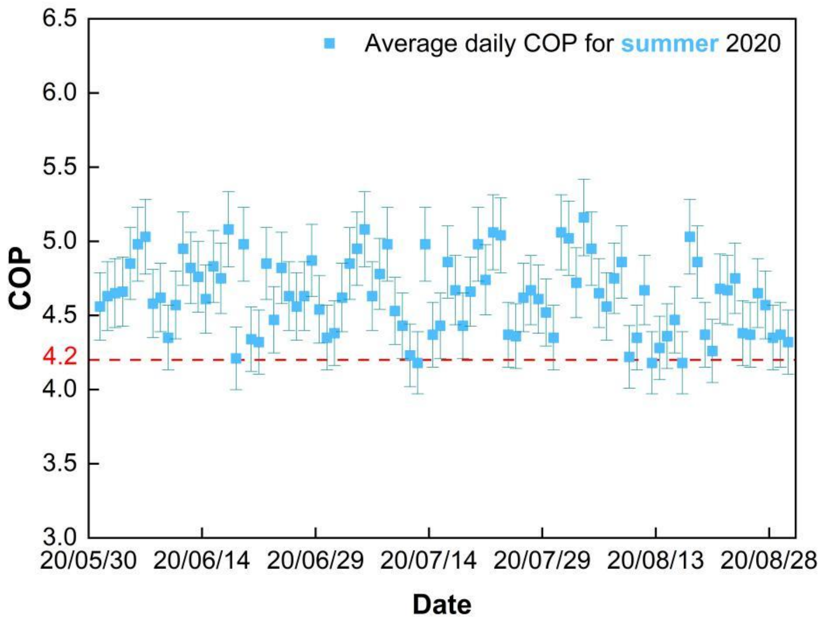


Fig 5-5 Average daily COP distribution under cooling conditions

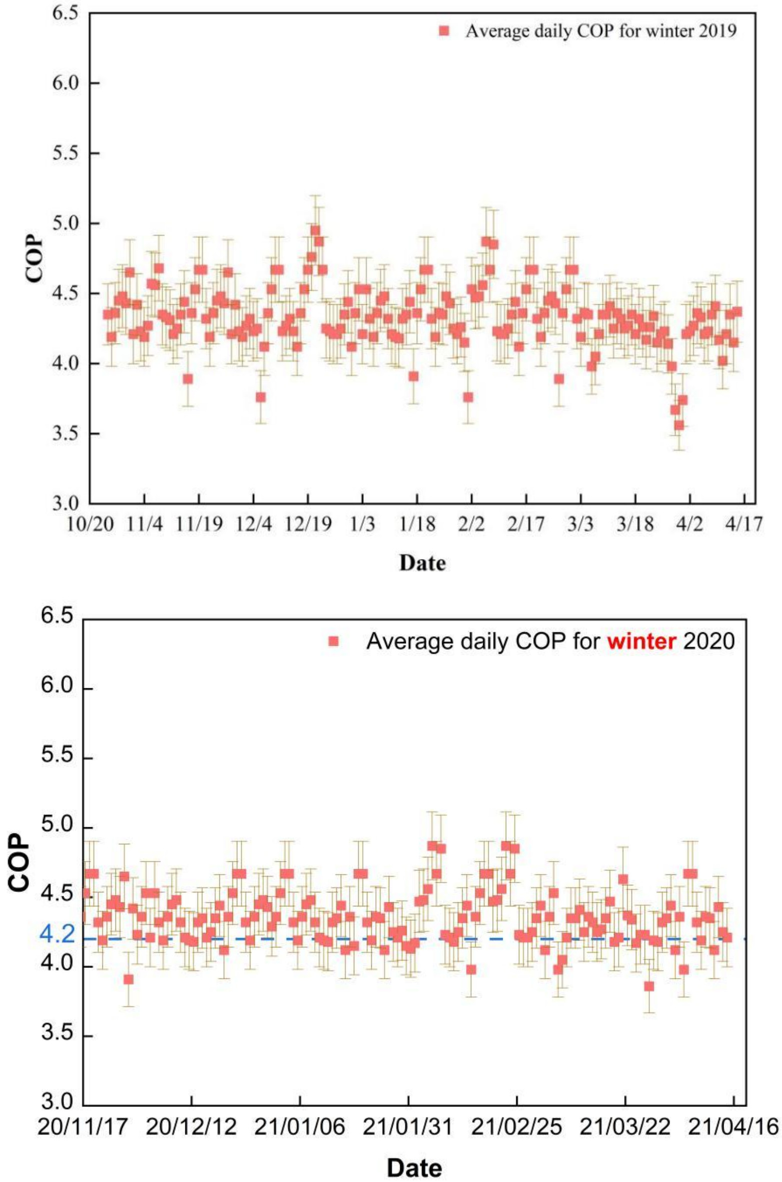


Fig 5-6 Average daily COP distribution under heating conditions

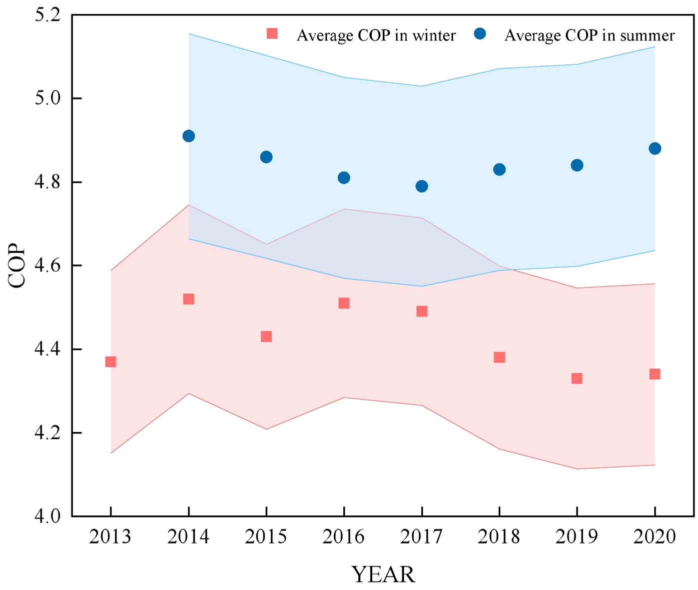
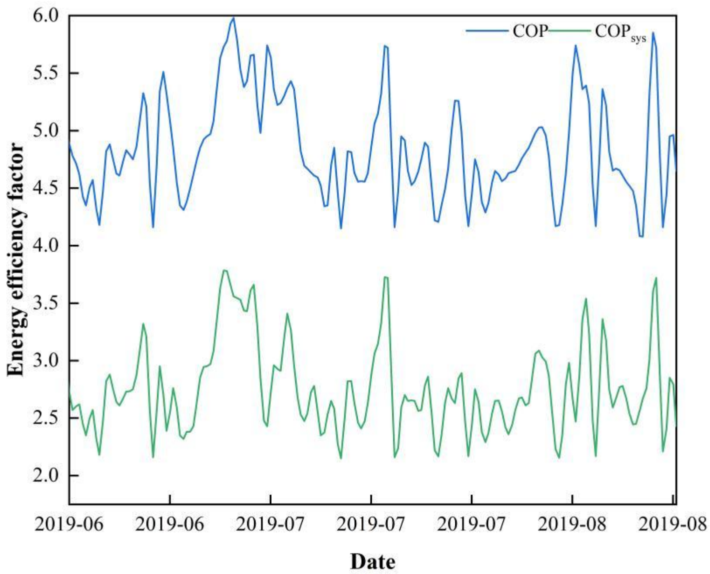


Fig 5-7 Average annual COP under cooling and heating conditions



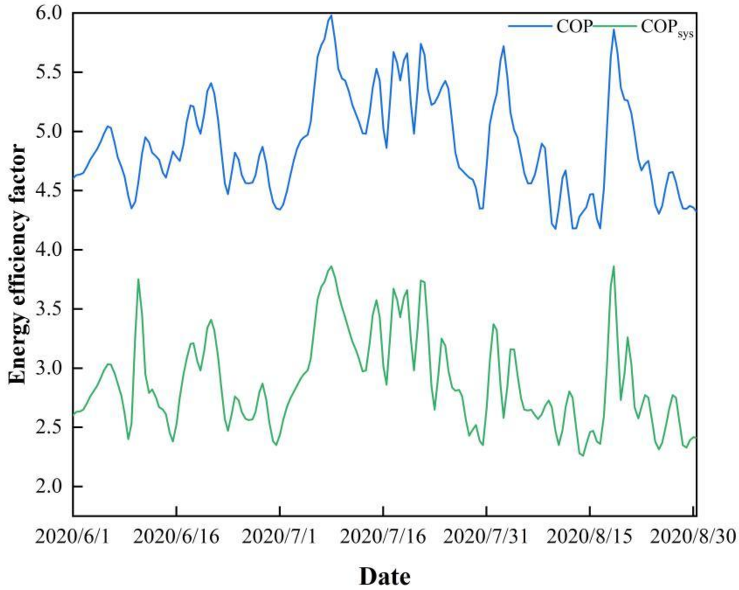
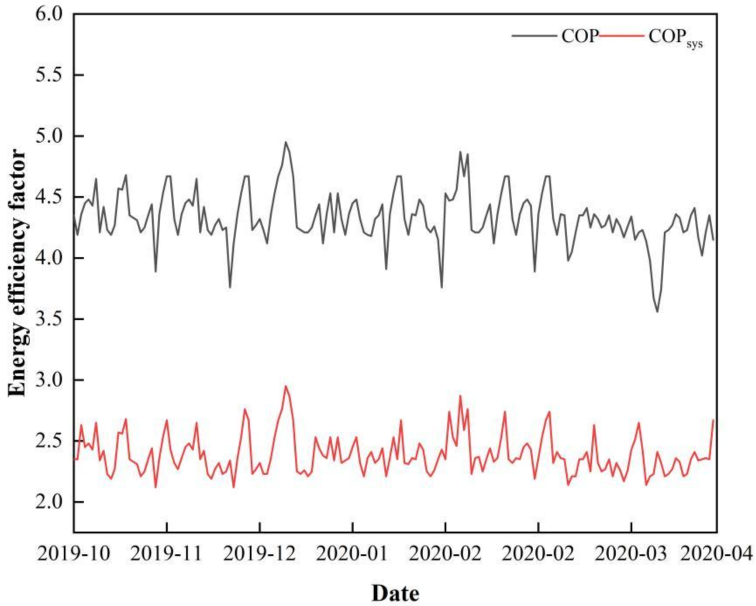


Fig 5-8 Energy efficiency factor in cooling conditions in 2019 and 2020



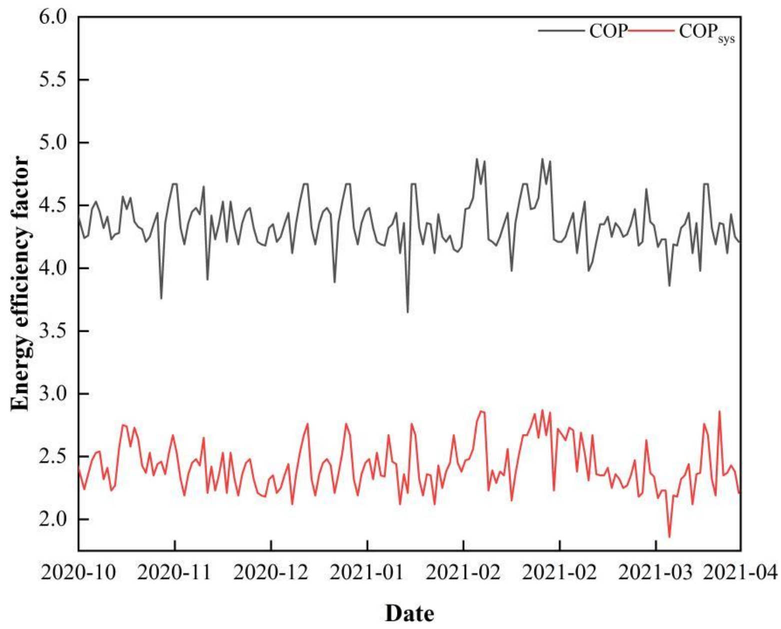


Fig 5-9 Energy efficiency factor in cooling conditions in 2019 and 2020

Using the data recorded by the monitoring system, the energy efficiency coefficient COP of the unit from winter 2013 to summer 2020 was calculated using equations (5-1), (5-2) and (5-3).The results are shown in Table 5-1, while the changes in the energy efficiency coefficient COPsys of the system are shown in Table 5-2.

From Table 5-1, it can be seen that the average COP of the unit under winter conditions shows a gradual decrease during the long-term operation. This decrease can be attributed to the continuous decrease of the water supply temperature on the ground source side with the long-term operation of the unit. In order to reach the designed water supply temperature, more energy is required, resulting in a decrease in the COP of the unit. Conversely, the average COP of the unit under summer operating conditions exceeded the COP under winter conditions.This difference was attributed to the cooler subsurface soil in the summer providing a more favorable operating environment, thereby improving the performance of the ground source heat pump (GSHP) system.

After 8 years of long-term operation, the COP of this system was determined to be 89.33% for winter conditions and 94.98% for summer conditions with a rated COP of 4.2. In addition, Table 5-2 shows that after 8 years of operation, considering a rated COPsys value of 2.2, the COPsys compliance of this system reached 96.88% for winter conditions and reaching 97.91%. These findings highlight the stable and energy-efficient operation of the unit and system over a longer period of time. The use of zonal thermal compensation technology in the system contributes to its efficient and prolonged operation, ensuring favorable energy savings and extending the overall system lifetime.

Table 5-1 Unit energy efficiency factor COP

Running time (winter)	COP variation range	Average COP	Rate of compliance (%)	Running time (summer)	COP variation range	Average COP	Rate of compliance (%)
2013	3.06-5.15	4.37	93.56	2013	-	-	-
204	3.51-5.38	4.52	95.27	2014	4.22-5.89	4.91	96.75
2015	3.78-5.22	4.43	93.68	2015	3.74-5.84	4.86	96.52
2016	3.42-5.15	4.51	92.71	2016	3.76-5.92	4.81	96.34
2017	3.39-5.16	4.49	91.26	2017	3.95-5.88	4.79	95.48
2018	3.48-5.01	4.38	91.18	2018	4.05-5.93	4.83	96.02
2019	3.56-4.95	4.33	89.97	2019	4.08-5.98	4.84	95.23
2020	3.65-4.84	4.34	89.33	2020	3.72-5.87	4.88	94.98

Table 5-2 System energy efficiency coefficient COPsys

Running time (winter)	COPsys variation range	Average COPsys	Rate of compliance (%)	Running time (summer)	COPsys variation range	Average COPsys	Rate of compliance (%)
2013	2.07-3.76	3.08	97.32	2013	-	-	-
2014	2.09-3.59	3.02	97.46	2014	2.86-3.68	2.95	98.36
2015	2.58-4.07	3.11	98.57	2015	2.51-3.49	2.82	97.78
2016	2.47-3.56	2.95	96.73	2016	2.66-3.74	2.95	97.86
2017	2.12-3.67	2.97	96.62	2017	2.95-3.89	3.18	98.55
2018	2.38-3.71	2.86	95.89	2018	2.78-3.88	2.98	97.72
2019	2.45-3.68	2.92	96.97	2019	2.61-3.79	2.93	96.89

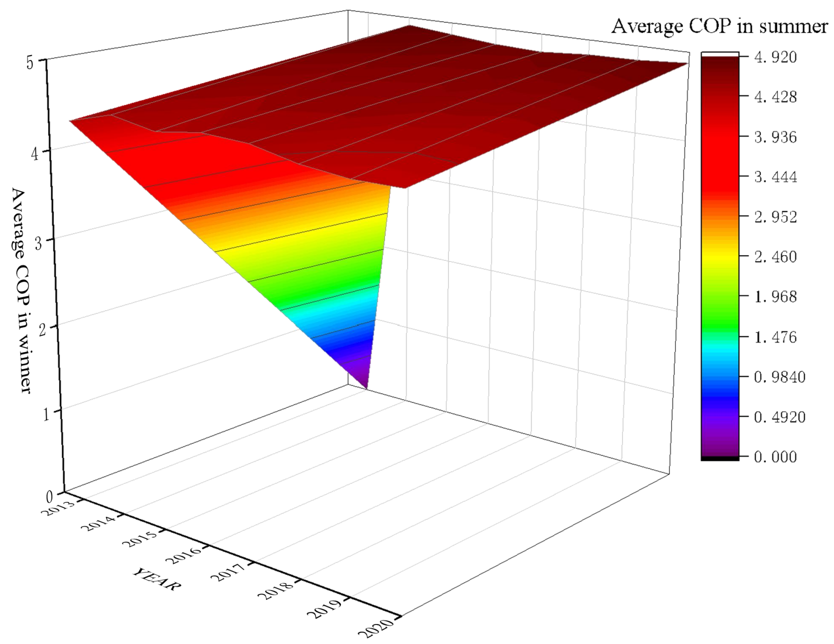


Fig 5-10 Average annual COP in 8 years of operation of GSHPs

5.4 Results and analysis of Performance simulation

In order to ensure the long-term efficient and stable operation of the ground source heat pump system in the cold region, the influence of the change of the average underground temperature around the buried pipe of the soil heat pump system on the energy efficiency of the system during the life cycle of the soil source heat pump system is further studied, and the simulation model of the ground source heat pump is established to introduce different loads and buried pipe temperature changes into the soil source heat pump module. The system simulation model is used to calculate the energy efficiency of the system in winter, namely COP value, when there is no compensation mode, there is corresponding refrigeration area compensation mode, and the heat pump is only used for heating. The change law of its life cycle is studied to guide the ground source heat pump project in cold region.

After the operation of the system is stable, the system is tested in summer cooling condition and winter heating condition. The test includes: indoor and outdoor temperature, inlet and outlet temperature and flow rate, chilled water supply and return water temperature and flow rate, heating circulating water supply and return water temperature and flow rate, heat pump power consumption and pump power consumption.

5.4.1 Effect of flow rate on COP

When the heat pump unit is running, if the flow rate is too low, it is not conducive to the safe operation of the unit; when the flow rate is too high, the power of the circulating pump will increase and the power consumption will increase. Assuming other conditions remain unchanged, the effect of water flow on the performance of the heat pump unit is analyzed. Under refrigeration conditions, when the radon flow of water is increased, the outlet water temperature of the heat exchanger will decrease, the heat exchange coefficient will increase, and the cooling capacity will increase. The amount of water will have a certain effect on the COP of the heat pump. As shown in Fig 5-11, during the cooling operation in summer, increasing the water flow of the cold condenser will lead to a reduction in the condensing pressure, which will reduce the input power of the compressor. However, when the water flow rate increases to a certain value, the rate of increase of the COP value tends to stabilize.

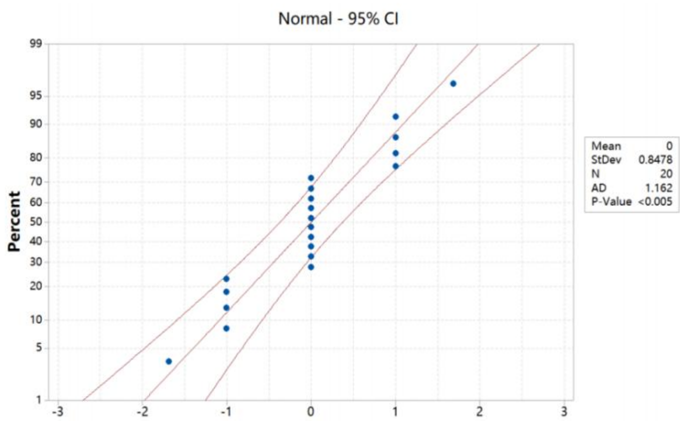


Fig 5-11 Effect of flow rate on COP

5.4.2 Changes and analysis of system COP when no compensation method is adopted

The project is located in the cold region. When the ground source heat pump system bears the same area of cooling and heating in winter and summer, the energy efficiency ratio of the system is greatly affected by the change in soil temperature, and there is a risk of energy efficiency reduction in successive years of operation. The performance of a heat pump can be assessed by the coefficient of performance (COP) of heat pump, which is the ratio of the useful energy obtained as output from the heat pump to the electrical energy given as input to the heat pump. Similarly, the energy efficiency of the GSHP system can also be measured by the COP of the system, which is the ratio of the use able energy output from the system to the overall electrical energy input to the system.

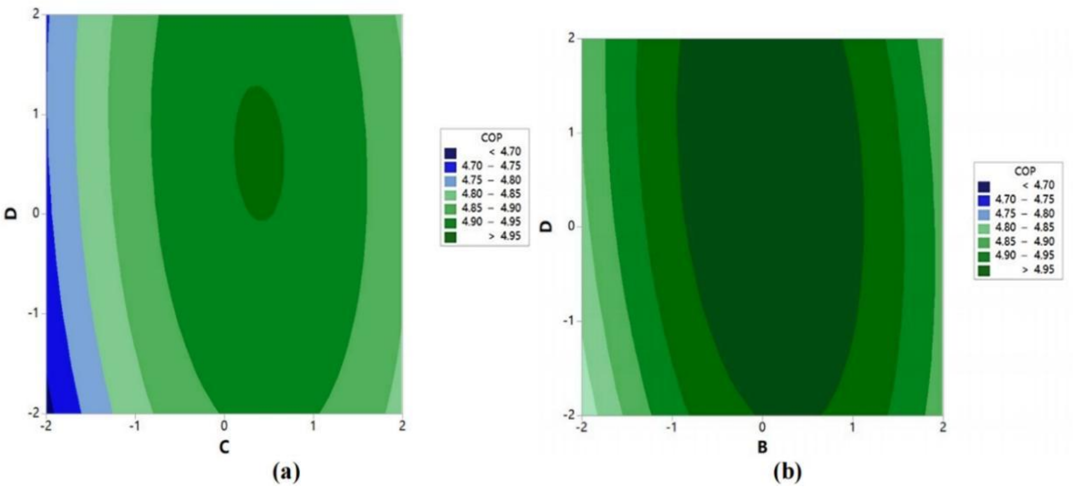


Fig 5-12 COP of Soil source heat pump system without compensation to run

Fig 5-12 shows that in the first year of operation, the average coefficient of performance (COP) for heating was recorded as 4.94. However, by year 5, the average energy efficiency ratio dropped to 3.90, further to 3.58 in year 9 and to 3.47 in year 13. It is noteworthy that the average energy efficiency decreases gradually each year as the soil temperature decreases. This decline is particularly pronounced in the first decade of operation, with an average annual decline of 0.15. In subsequent years (10-13), the average COP under winter conditions decreases by 0.02 per year. thus, by year 13 of operation, the system COP decreases from approximately 5.0 to less than 3.5. this decline in energy efficiency as soil temperature decreases is not conducive to the desired energy savings of ground source heat pump systems characteristics. This side effect became apparent after several years of operation. By the 13th year, the system could no longer be considered an energy efficient heating solution.

5.4.3 Change and analysis of system COP with corresponding area compensation

In the case of corresponding area compensation, generally speaking, in the case of corresponding area compensation, the soil temperature does not change much, which has little effect on the COP of the system. Efficient and stable energy-saving operation is realized. In the first year of operation, the average COP value of heating in winter was 4.94 (Fig 5-13). In the first 13 years of operation, the energy efficiency ratio of the winter system was reduced to 4.61, the average annual decrease was 0.03. Efficient and energy-saving operation is present.

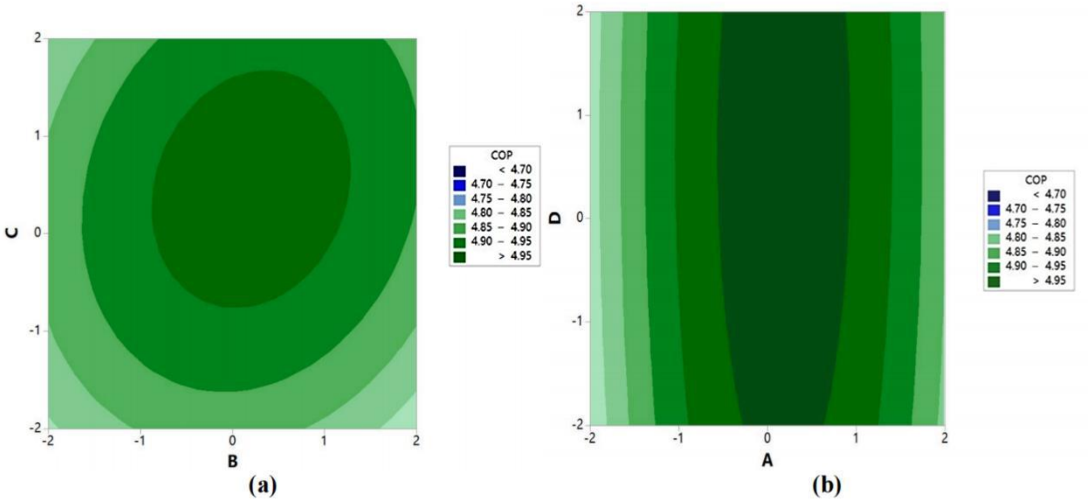


Fig 5-13 COP of Soil source heat pump system with area of compensation to run

5.4.4 Only used for heating system COP change and analysis

When the soil source heat pump system is only used for heating in winter, because the system continuously absorbs heat from the ground, only relying on the temperature selfrecovery ability of the underground constant temperature soil heat storage body to compensate the soil temperature, resulting in the continuous decrease of the average soil temperature, the system COP The impact is extremely significant. The ground source heat pump system maintains a high COP of 4.87 in the first year, and the COP of the system in the fifth year of operation has been reduced to 3.13, which greatly affects the energy saving of the system (Fig 5-14). The original intention of applying the ground source heat pump system for high efficiency and energy saving.

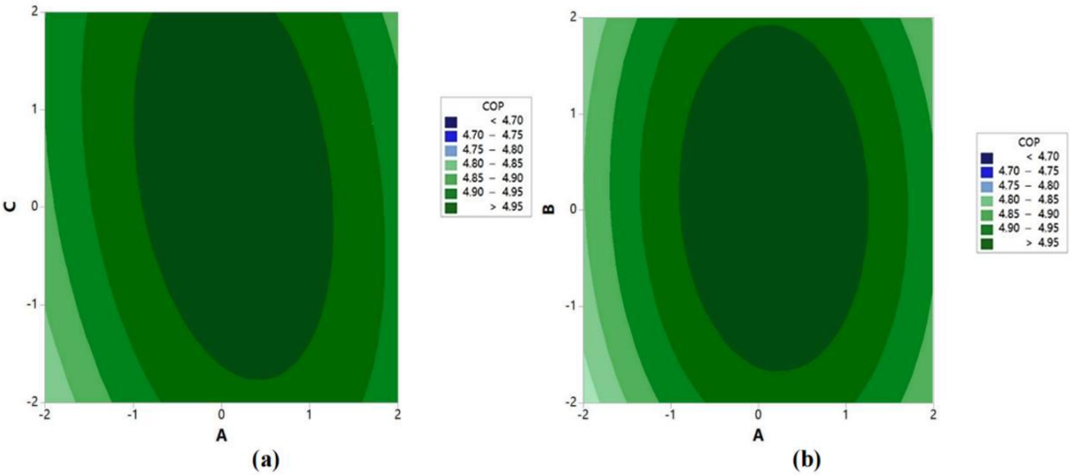


Fig 5-14 Only used for heating system COP change and analysis

From the comparison of the three cases, it can be seen that COP changes rapidly in the first 10 years of operation, especially in the first 5 years, while it changes steadily in the second 20 years of operation. When only the soil source heat pump system is used for heating, the COP of the system decreases from 4.87 to 3.13 in the fifth year of operation, which seriously affects the energy efficiency of the system. In the heat pump system with the same cooling and heat load area, the COP value of the heat pump system with outstanding soil thermal imbalance dropped below 3.5 in the 13th year of operation. The energy-saving effect is no longer obvious. The average annual decrease of COP in winter was about 0.01 when reasonable cooling area compensation was adopted. After 30 years of operation, COP value of heating system is still maintained at 4.5, which solves the problem of soil heat imbalance.

Table 5-3 Winter system COP value three operating condition changes

Winter system COP	Winter and summer bear the same area	In the case of area compensation	Only the heating conditions are considered
Run year 1	4.93	4.95	4.87
Run year 3	4.18	4.73	3.61
Run year 5	3.90	4.69	3.13
Run year 10	3.57	4.61	-
Run year 20	3.34	4.52	-
Run year 30	3.27	4.50	-
Average annual decline	0.06	0.01	-

Through the comparison of the three cases, the effectiveness of controlling the proportion of the system burden area in winter and summer to solve the problem of soil heat imbalance was verified. The self-compensation ability of soil temperature reflected by the transition soil temperature rise and the reduction of annual temperature drop in the next 30 years could not be ignored.

5.5 Energy efficiency analysis of GSHPs

5.5.1 Primary Energy Utilization

Primary energy utilization, or energy utilization factor, refers to the utilization of primary energy, and a larger value indicates a more adequate utilization of primary energy by the system.

For power generation, this paper considers coal-fired power plants, which are currently the main power generators. The thermal efficiency of coal-fired power plants is converted according to the standard coal consumption of 307 g/(kW-h) for 6,000 kW and above units nationwide in 2019 released by the National Energy Administration; the loss rate of power supply lines is also calculated according to 5.9% in 2019 released by the National Energy Administration. The flow and nodes of the energy state change are shown in Fig 5-15. The relevant parameters of each node are distinguished by node serial numbers as subscripts.

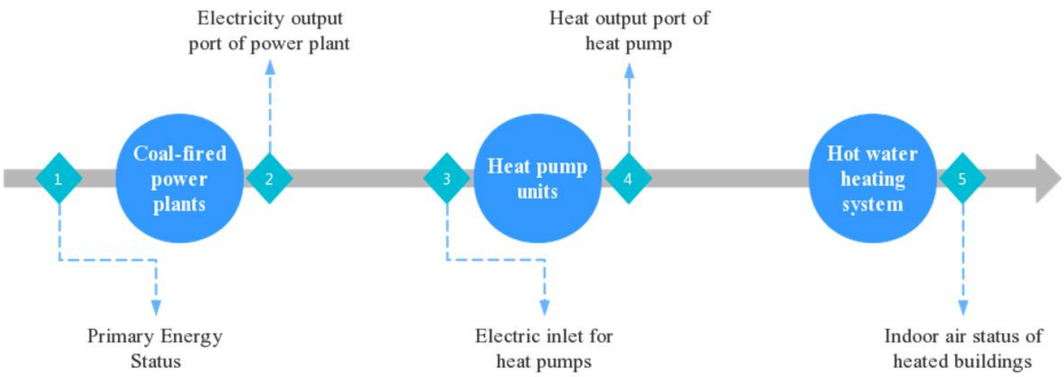


Fig 5-15 Flow and nodes of energy state change

A heat pump unit is regarded as a overall, its output heat is Q4, the electricity consumption of the unit is W, the heat generated by combustion of primary energy consumption corresponding to W is Q1, the electricity at the outlet of the power plant corresponding to W is Q2 (the value of the heat contained is the same), the input power of the heat pump Q3 = W (the value of the heat contained is the same), then there is the following relationship between them:

$$Per = \eta_{th}\eta_1\eta_2 COP \quad (5\text{-}4)$$

$$Q_2 = \eta_f Q_1 \quad (5\text{-}5)$$

$$Q_3 = \eta_x Q_2 = \eta_f \eta_x Q_1 \quad (5\text{-}6)$$

$$Q_4 = \eta_f \eta_x COP Q_1 \quad (5\text{-}7)$$

where η_f is the thermal efficiency of the power plant; η_x is the efficiency of the supply line; COP is the performance coefficient of the heat pump unit.

where η is related to the loss rate X of the supply line as follows:

$$\eta_x = (100 - X) \times 100\% \quad (5\text{-}8)$$

$$COP = \frac{Q_4}{W} = \frac{Q_4}{Q_3} \tag{5-9}$$

Then the primary energy thermal efficiency of the heat pump unit η

$$\eta_i = \frac{Q_1}{Q_1} = \eta_i \eta_{\times} COP$$

(5-10)

From Equation (5-4), it can be seen that the primary energy utilization is mainly related to the unit performance parameter COP, The ground source heat pump heating has a heat network efficiency of 0.98 and a power supply efficiency of 0.35. The product of η_1 and η_2 is the power supply efficiency [45]. The primary energy utilization rate calculated from the monitoring data of the ground source heat pump system in Chapter 3 is shown in Table 5-4.

The primary energy utilization rate of the system is calculated to be 1.516 in winter conditions and 1.662 in summer conditions. Table 4-3 lists the primary energy utilization rates of several different heating methods, and the average primary energy utilization rate of the system is 1.516 in winter conditions, which is higher than that of boiler heating system, electric heating and air source heat pump system.

Table 5-4 Unit COP and primary energy efficiency

Running time (winter)	Average COP	Primary Energy Utilization	Running time (summer)	Average COP	Primary Energy Utilization
2013	4.37	1.49891	2013	-	-
2014	4.52	1.55036	2014	4.91	1.68413
2015	4.43	1.51949	2015	4.86	1.66698
2016	4.51	1.54693	2016	4.81	1.64983
2017	4.49	1.54007	2017	4.79	1.64297
2018	4.38	1.50234	2018	4.83	1.65669
2019	4.33	1.48519	2019	4.84	1.66012
2020	4.34	1.48862	2020	4.88	1.67384

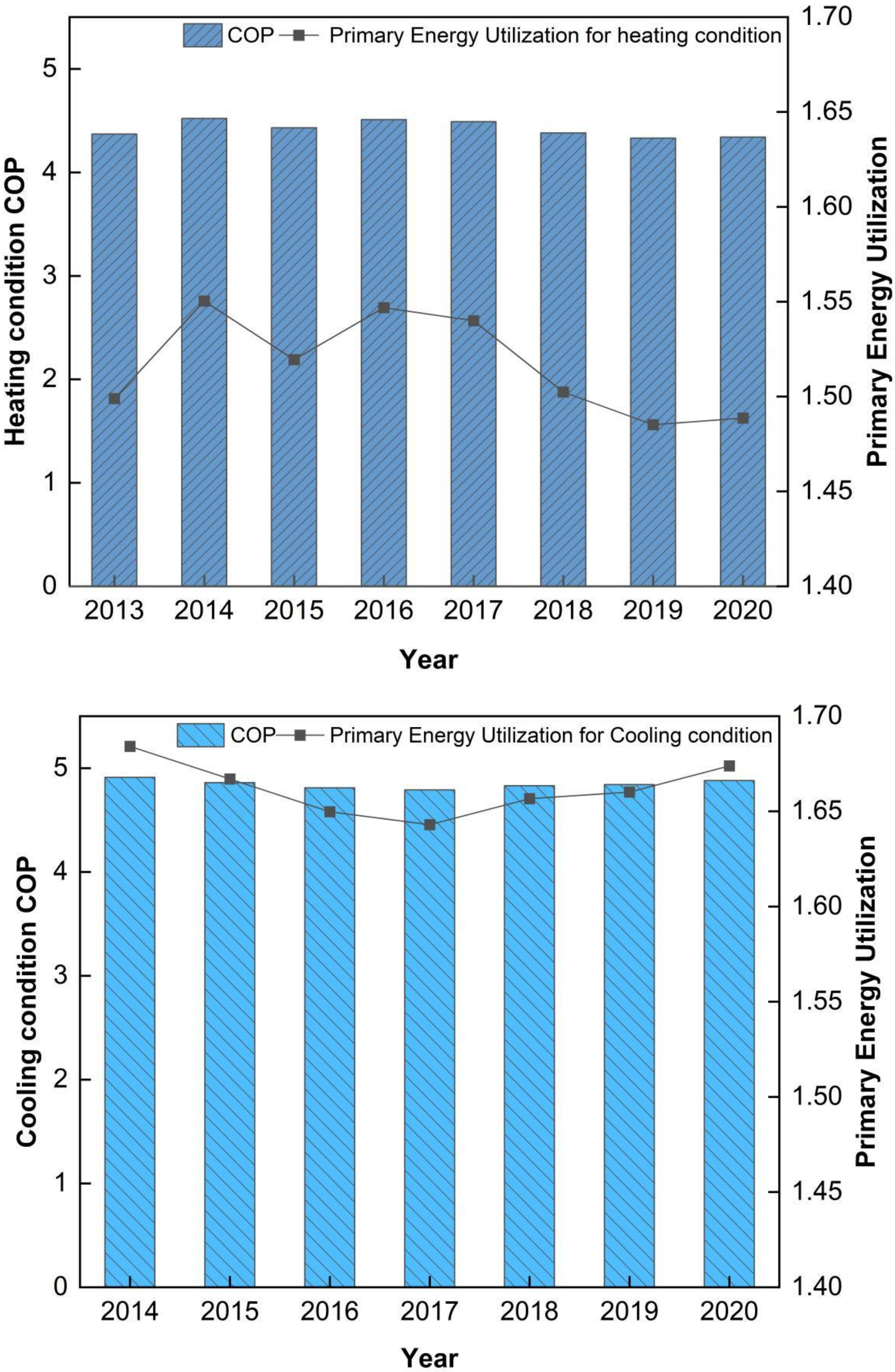


Fig 5-16 Primary energy rate for heating and cooling conditions

The average primary energy efficiency rate of this system is 1.51 in winter conditions and 1.66 in summer conditions. Table 5-5 lists the primary energy efficiency rates of several different heating methods, and the primary energy efficiency rate of this system in winter conditions is higher than that of boiler heating system, electric heating and air source heat pump system.

Table 5-5 Primary energy efficiency of several different systems

Form of heating system	Primary energy efficiency
Boiler heating	0.56
Electric heating	0.39
Air source heat pumps	0.89

5.5.2 Conventional energy replacement volume and energy saving rate

The conventional energy replacement and energy saving rate equations for the soil source heat pump system are shown in (5-11) and (5-12). The energy efficiency value of the unit has been calculated in the previous paper, and the building load is calculated from the environmental parameters. and the highest value of temperature is 34.4℃ and the lowest value is 28.1℃; and the maximum value of total radiation is 30.86MJ/m^2 and the minimum value is 0. The transformation range is normal. In the cold region, the heat load in winter is much larger than the cold load in summer. After adopting the ground source heat pump system, the heating and cooling areas in winter and summer are different, so the hot and cold loads are more balanced. The maximum cooling load occurs in July, with a total monthly load of 164.3MWh and a peak load of 463.6kW.

By comparing with the conventional heating boiler system, the annual coal saving of GSHP is calculated. Equation (5-11) for converting energy consumption and standard coal of the heat pump system:

$$C_S = 3.6\frac{E_H}{\eta c} \tag{5-11}$$

Conventional boiler room heating energy consumption is converted into standard coal calculation Equation:

$$C_{\text{bS}} = 3.6\frac{Q_H}{c\eta_b} + \kappa C_s \tag{5-12}$$

The difference between Equation (5-11) and (5-12) is the standard coal saving amount in heating condition (5-13) :

$$\Delta C_{s1} = C_{bs} - C_s$$

Where: CS is heat pump heating consumption converted standard coal amount, t; EH is annual energy consumption of heat pump system, kW • h; η is electrical energy conversion rate, %; c is standard coal heat, kJ/kg.Cbs is converted into standard coal consumption in boiler heating form, t; QH is Building annual cumulative heat load, kW •h; η b is electrical energy conversion rate, %; c is standard coal heat, kJ/kg; κ is Energy consumption ratio of end-circulating pump to system.

Annual cooling standard coal saving:

Compared with the conventional chiller, calculate the annual refrigeration coal saving. The energy consumption of the heat pump system is converted into standard coal calculation Equation (5-14) :

$$C_L = 3.6\frac{E_L}{\eta c} \tag{5-14}$$

The energy consumption of conventional chiller is converted into standard coal calculation

Equation:

$$C_{\mathrm{CL}} = 3.6\frac{Q_L}{COP\eta c} \tag{5-15}$$

The difference between Equation (5-14) and (5-15) is the standard coal saving amount:

$$\Delta C_{S2} = C_{CL} - C_L \tag{5-14}$$

The total section coal computation:

$$\Delta C_S = C_{S1} + C_{S2} \tag{5-15}$$

Energy saving rate calculation: $\zeta = \frac{\Delta C_S}{C_{bs}+C_{CL}} \times 100\%$

Where: C_L is converted into the standard coal consumption of heat pump cooling, t; E_L is Annual cooling power consumption of heat pump system, kW • h; η is electrical energy conversion rate, %; c is standard coal heat, kJ/kg; C_{CL} is converted into the standard coal consumption of water chiller, t; Q_L is Building annual cumulative cooling load, kW • h; COP is coefficient of refrigeration performance of conventional systems.

The total load sink of the system from winter operation in 2013 to winter in 2020 is substituted into the formula to calculate the conventional energy replacement and energy saving rate of the system, and the calculated results are summarized in Table 5-6 below.

Table 5-6 Energy efficiency assessment table

Running time (year)	Energy saving (tons of standard coal)	Energy saving rate
2013 (Winter)	50.92	56.3%
2014(Summer)	35.13	47.9%
2014(Winter)	50.22	54.8%
2015(Summer)	36.54	49.3%
2015(Winter)	45.45	50.2%
2016(Summer)	35.85	48.2%
2016(Winter)	48.54	52.7%
2017(Summer)	36.72	49.5%
2017(Winter)	50.65	55.2%
2018(Summer)	34.98	46.5%
2018(Winter)	47.88	52.3%
2019(Summer)	35.47	47.6%
2019(Winter)	48.36	51.8%
2020(Summer)	36.11	48.6%
2020(Winter)	46.72	50.8%

The system started to operate in winter of '13, and the energy saving rate value was high at the beginning of the operation. Starting from summer of '14, the energy saving rate of the system showed a decreasing trend, but the magnitude was small, and the average energy saving rate of the system was 53% in winter conditions and 48.2% in summer conditions, so the energy saving effect of the system was remarkable.

5.6 Exergy efficiency analysis of GSHPs

After the heat pump unit, the system input is transported to the end user by the transport pipeline, and during the transport process, the energy quality will be continuously reduced and dissipated to the environment. Considering the whole process as composed of cold and heat units, conveying units and end units, when performing the calculation of the radiant analysis, the energy starts from cold and heat sources through different transformations, and the energy quality decreases continuously until it is dissipated to the user's environment.

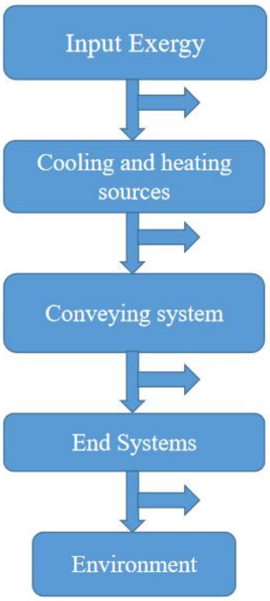


Fig 5-17 Schematic diagram of exergy efficiencies of GSHP system

5.6.1 Exergy Analysis of heat pump unit

In recent years, many scholars have started to analyze exergy efficiencies of ground source heat pump units, but most of them focus on water source heat pumps [46], and there are fewer studies on soil source heat pumps, and all of them focus on heating conditions due to the specificity of the climate, and almost no one has performed a complete R&D analysis due to the specificity of the climate in cold regions. Therefore, in this section, the complete energy use analysis of each component in the system, the refrigerant circulation loop and the water circulation loop is carried out to obtain the various indexes for the analysis of the exergy efficiencies under the two working conditions of heating and cooling.

As described in Chapter 3, the heat pump units of this demonstration project use the high-efficiency environment-leading HFC410A refrigerant, each unit consists of two compressors with an input power of 76 kW, the average temperature of chilled water inlet and outlet is 40.6° C, and the inlet and outlet temperature of the buried pipe side is 11.8° C. The soil source heat pump system was analyzed by real-time monitoring of the state parameters at each state point of the system, and the soil source heat pump system was analyzed in heating and cooling conditions, respectively.

(1) Heat production conditions

Exergy efficiencies:

$$\mu_{r,l} = \frac{E_Q}{\frac{W}{\eta_C}+E_Q} = \frac{\left(1-\frac{T_0}{T_d}\right)Q}{\frac{W}{\eta_C}+\left(1-\frac{T_0}{T_q}\right)Q} = \frac{\varphi\left(1-\frac{T_0}{T_d}\right)cop}{1+\varphi\left(1-\frac{T_0}{T_q}\right)cop} \tag{5-16}$$

Exergy loss rate:

$$d_{r,l} = \frac{(1-\mu_{r,l})E_K}{(1-\mu_{sys})E_K} = \frac{1-\mu_{r,l}}{1-\mu_{sys}} \tag{5-17}$$

Loss factor:

$$\Omega_{r,l} = 1 - \mu_{r,l} \tag{5-18}$$

When analyzing the heat pump unit, the three evaluation indexes of heat efficiency, heat loss rate and heat loss coefficient are needed. Under the heating condition, the average energy efficiency of the heat pump unit is 3.88, the average temperature of chilled water import and export is 40.6 ℃, and the temperature of cooling water import and export is 11.8 ℃, and the calculation results are summarized in Table 5-7. The calculated efficiency of the heat pump unit is 22.78%, the heat loss rate is 83.73%, and the heat loss coefficient is 75.86%, which can be seen that the heat efficiency of the unit is low because the heat pump unit consumes more power, thus causing the heat loss rate and heat loss coefficient to be higher.

Table 5-7 Results of GSHP exergy efficiencies under Heat production conditions

Operation mode	Exergy efficiencies	Exergy loss rate	Loss factor
Heating conditions	22.78%	83.73%	75.86%

From the formula , it can be seen that the heat pump unit's efficiency is related to the unit's energy efficiency value, the average temperature of condenser inlet and outlet, and the average temperature of evaporator inlet and outlet. Assuming that the average temperatures of evaporator and condenser inlet and outlet in the unit remain unchanged, when the energy efficiency value of the unit is changed from 3.5 to 4.5, the heat pump unit's heat efficiency increases from 21% to 28%, and the change law is shown in Figure 5-18, and when the energy efficiency value of the unit is increased by 0.1, the unit's heat efficiency can be increased by 0.7%.

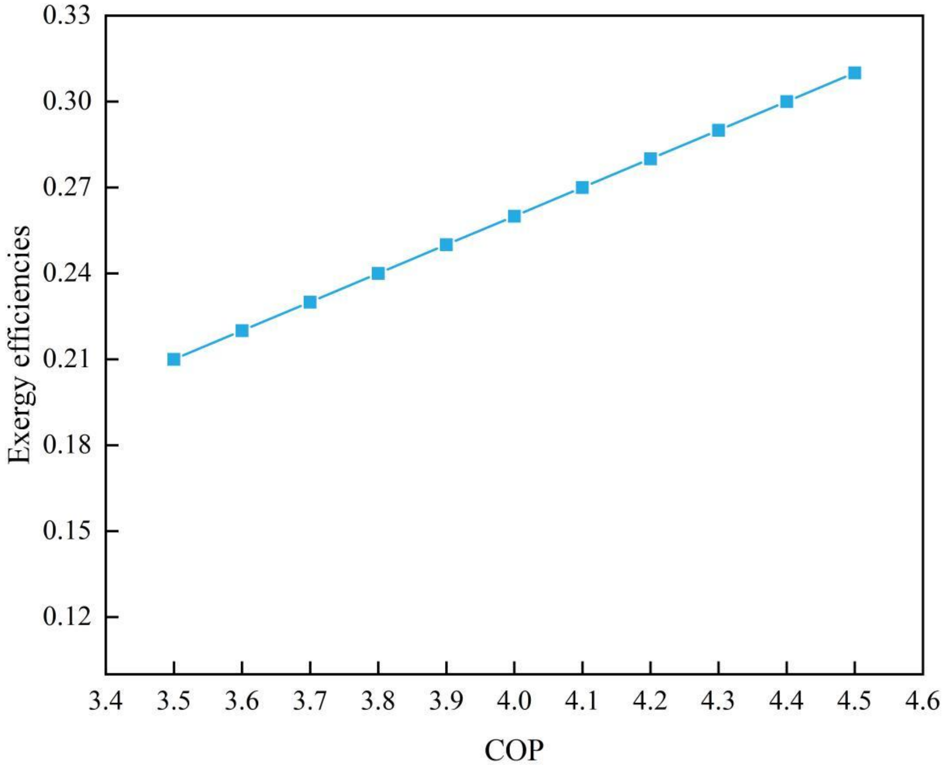


Fig 5-18 Variation law of exergy efficiency of random group of unit efficiency

Assuming that the average energy efficiency value of the heat pump unit in winter is 3.88 unchanged, the relationship between the changes in the import and export temperatures of the evaporator and condenser and the unit's brane efficiency is calculated and summarized as shown in Table 5-8, when the condenser import and export temperatures of the unit remain unchanged, the average temperature of the evaporator import and export increases from 9℃ to 13℃, the unit's brane efficiency decreases by 1% on average; when the evaporator import and export temperatures remain unchanged, the average temperature of the condenser import and export increases from When the average temperature of condenser inlet and outlet increases from 36℃ to 40℃, the average efficiency of the unit will increase by 4%. Therefore, we can improve the efficiency of the heat pump unit by improving the energy efficiency of the unit, i.e., appropriately increasing the temperature difference between the import and export of the ground source side and the user side, or making the unit operate at a higher load rate, so as to achieve the purpose of improving the efficiency of the heat pump unit.

Table 5-8 Change of exergy efficiency of heat pump unit with temperature

Average temperature of condenser inlet and outlet(℃)	Average temperature of the inlet and outlet of the evaporator (℃)				
Exergy efficiency	9	10	11	12	13
36	22.25%	21.83%	21.66%	21.29%	21.17%

37	23.19%	22.89%	22.71%	22.42%	22.18%
38	24.22%	23.92%	23.67%	23.33%	23.18%
39	25.25%	24.91%	24.66%	24.34%	24.14%
40	26.26%	25.93%	25.58%	25.36%	24.95%

(2) Cooling conditions

Under the cooling condition, the exergy efficiency of the soil source heat pump unit relative to the whole system, the exergy loss rate and the loss coefficient also need to be calculated separately again, and the formula for the analysis of the cold unit performance is as follows

Exergy efficiencies:

$$\mu_{r,l'} = \frac{E_Q}{\frac{W}{\eta_C}+E_Q} = \frac{\left(\frac{T_0}{T_d}-1\right)Q}{\frac{W}{\eta_C}+\left(\frac{T_0}{T_q}-1\right)Q} = \frac{\varphi\left(\frac{T_0'}{T_d'}-1\right)EER}{1+\varphi\left(1-\frac{T_0'}{T_q}\right)EER} \tag{5-19}$$

Exergy loss rate:

$$d_{r,I}' = \frac{(1-\mu_{r,I}')E_K}{(1-\mu_{sys})E_K} = \frac{1-\mu_{r,l}'}{1-\mu_{sys}} \tag{5-20}$$

Loss factor:

$$\Omega_{r,l}{}' = 1 - \mu_{r,l}{}' \tag{5-21}$$

Similar to the calculation of the heating system, the average energy efficiency of the heat pump unit under the cooling condition is 3.35, the evaporator inlet and outlet temperature is 10.31 ℃, the average condenser inlet and outlet temperature is 29 ℃, and the heat pump unit's assembly efficiency is 18.12%, the assembly loss rate is 84.51%, the assembly loss coefficient is 81.67%, and the assembly efficiency value of the heat pump unit under the summer condition is still low The results of the analysis of the heat pump unit in summer conditions are shown in Table 5-9.

Table 5-9 Results of GSHP exergy efficiency under Cooling conditions

Operation mode	Exergy efficiency	Exergy loss rate	Loss factor
Cooling conditions	18.12%	84.51%	81.67%

The exergy efficiency of the heat pump system in summer condition is 19.2%, which is lower than that of the heat pump system in summer condition, and therefore the reason is similar to that of the heat pump system in winter condition, so it is not specified here. Since the heat pump unit's efficiency is related to the cooling coefficient, cooling water and chilled water average temperature of the unit, the heat pump unit's efficiency changes with the unit's energy efficiency in summer are plotted as the curve shown in Fig 5-16, which shows that when the heat pump unit's energy efficiency value changes from 3 to 4, the unit's efficiency increases from 17% to 23%, that is, when the heat pump unit's energy efficiency value increases by 0.1, the unit's efficiency increases by 0.6%. Therefore, whether in winter or summer conditions, improving the energy efficiency coefficient of heat pump units is an effective way to improve the efficiency of the heat pump units.

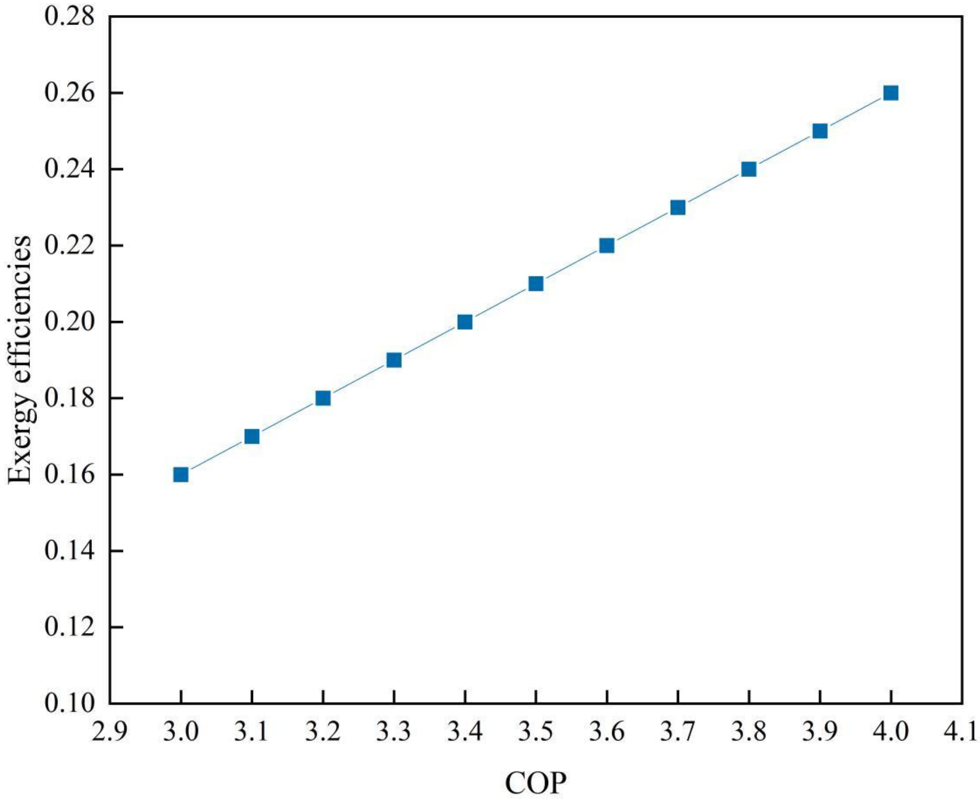


Fig 5-19 Variation law of exergy efficiency of random group of unit efficiency

Through the comparison, it is found that the calculation results in winter and summer are similar, and the ground source heat pump unit has a lower value of the efficiency of the heat pump unit. The main factors affecting the efficiency of the unit are the energy efficiency value of the unit, the average temperature of the chilled water inlet and outlet, and the average temperature of the cooling water inlet and outlet. Since the energy efficiency value of the soil source heat pump unit in the heating condition is larger than that in the cooling condition, the efficiency of the heat pump unit in winter is larger than that in summer, as obtained in the energy efficiency analysis of the soil source heat pump unit in the previous section. Therefore, we can improve the efficiency of the heat pump unit by improving the energy efficiency of the unit, and then improve the mainline efficiency of the system.

5.6.2 Analysis of transport pipeline exergy efficiency

The conveying unit of ground source heat pump system is the intermediate conveying pipe connecting the heat pump unit and the end fan coil. When the pipe conveys the liquid mass, there will be certain heat loss due to the heat exchange with the outside world.

Transport pipeline exergy equation:

$$RL|T - T_0| = cm(T_2 - T_1) \tag{5-22}$$

$$T_2 = T_1 - \frac{RL|T-T_0|}{\mathrm{cm}} \tag{5-23}$$

The transport pipeline is in exergy balanced equation:

$$E_1 = E_2 + E_s \tag{5-24}$$

Exergy efficiency:

$$\mu_{e,s} = \frac{(T_2 - T_0) - T_0 \ln\frac{T_2}{T_0}}{(T_1 - T_0) - T_0 \ln\frac{T_1}{T_0}} \tag{5-25}$$

Exergy loss rate:

$$d_{e,s} = \frac{(1-\mu_{e,s})\mu_{r,l}}{1-\mu_{sys}} \tag{5-26}$$

Loss factor:

$$\Omega_{e,s} = 1 - \mu_{e,s} \tag{5-27}$$

From the analysis model of the heat transfer unit, we can see that if we need to analyze the heat transfer pipeline, we need to know the import and export temperature of the liquid mass, and the import temperature of the liquid under the heating condition is 319.85 K and the export temperature is 317.05 K. The import temperature of the liquid under the cooling condition is 280.29 K and the export temperature is 281.27 K. The efficiency of the heat transfer pipeline is calculated by substituting the formula 92.,69 %, the ratio of heat loss is 1.9%, and the coefficient of heat loss is 7.31%; the heat efficiency of conveying pipeline under refrigeration condition is 90.4%, the ratio of heat loss is 10.28%, and the coefficient of heat loss is 1.98%, and the results of heat analysis of conveying pipeline are shown in Table 5-10.

Table 5-10 Results of GSHP exergy efficiency under Cooling conditions

Operation mode	Exergy efficiency	Exergy loss rate	Loss factor
Cooling conditions	90.4%	1.98%	9.6%
Heating conditions	92.69%	1.9%	7.31%

The results show that the efficiency of the heat dissipation of the pipeline in winter condition is 92.69%, and the efficiency of the pipeline in summer condition is 90.4%, which are higher than 90%, and the heat dissipation rate does not exceed 2%, which means the heat dissipation loss of the pipeline is very small. The main reason for the heat loss of conveying pipeline is that there is a certain pressure drop due to the resistance of refrigerant in the process of flowing in the pipeline, and the effective way to reduce the heat loss of pipeline is to reduce the flow resistance and design the pipeline reasonably.

5.6.3 Analysis of extension coils exergy efficiency

Fan coils, radiators, geothermal coils and other end units can realize heat exchange with the environment. The end unit of the soil source heat pump system used in this demonstration project refers to the fan coils installed on the user's side, which will lose a certain amount of heat when exchanging heat with the indoor environment, and therefore will cause a loss of heat and humidity, and may also cause a certain amount of heat loss due to insufficient heat exchange of fan coils.

Transport pipeline exergy equation:

$$E_1 = E_2 + E_f + E \tag{5-27}$$

Workpiece importation of exergy:

$$E_1 = C_p(T_1 - T_0) - C_p T_0 \ln \frac{T_1}{T_0} \tag{5-28}$$

The indoor obtained value of the raining:

$$E = C_p(T_1 - T_0)\left(1 - \frac{T_0}{T_{\text{room}}}\right) \tag{5-29}$$

The efficiency of the blower coils in the room:

$$\mu_{e,m} = \frac{(T_1 - T_0)\left(1 - \frac{T_0}{T_{\text{room}}}\right)}{(T_1 - T_0) - T_0 \ln \frac{T_1}{T_0}} \tag{5-30}$$

The rate of loss of the wind turbine coils:

$$d_{e,m} = \frac{(1 - \mu_{e,m})\mu_{r,l}\mu_{e,s}}{1 - \mu_{sys}} \tag{5-31}$$

The heat loss coefficient of fan coils:

$$\Omega_{e,m} = 1 - \mu_{em} \tag{5-32}$$

By monitoring the liquid import and export temperature and the ambient temperature, the ambient temperature is 291.15K, the room temperature is 296.15K, and the terminal mass inlet temperature is 317.05K under winter conditions, and the efficiency of fan coil under heating conditions is 40.19%, the loss rate is 65.61%, and the loss coefficient is 14.44% under summer conditions. loss coefficient is 14.44%; the ambient temperature is 303.55K, the room temperature is 299.15K, and the inlet temperature of the terminal mass is 281.27K under the summer working condition, and the heat efficiency of the fan coil is 38.1%, the heat loss rate is 11.52%, and the heat loss coefficient is 61.9% under the cooling working condition, although its heat efficiency is higher than that of the heat pump unit, it is lower than the heat efficiency of the conveying pipe. Although its efficiency is higher than that of the heat pump unit, it is lower than that of the pipeline. The results of the analysis of the fan coil are summarized in Table 5-11.

Table 5-11 Results of fan coil units exergy efficiencies

Operation mode	Exergy efficiency	Exergy loss rate	Loss factor
Cooling conditions	38.1%	11.52%	61.9%
Heat production conditions	40.19%	14.44%	59.81%

Comparing the results of the analysis of the humidity of the fan coil in winter and summer, it can be seen that the system radiation efficiency in winter condition is 40.19%, and the radiation efficiency in summer condition is 38.1%, which is due to the colder winter, the room temperature required is higher, resulting in its higher radiation efficiency, and it is found in the study that the classroom doors and windows are often opened in summer, which causes the ambient temperature to rise continuously, and the difference between the inlet temperature of the working mass is getting bigger and bigger. Thus, it causes the fan coil to have a lower efficiency in the summer working condition.

From the formula, it can be seen that the efficiency of the fan coil is related to the inlet temperature, room temperature and ambient temperature, when the room temperature rises, the efficiency of the fan coil will rise, the ambient temperature and the efficiency of the fan coil is shown in Figure 4-20, when the room temperature rises from 20℃ to 25℃, the efficiency of the fan coil is increased from 16% to 55.9%. The influence of room temperature on the efficiency of fan coil is very significant; and the closer the temperature of work material is to the ambient temperature, the higher the efficiency of fan coil.

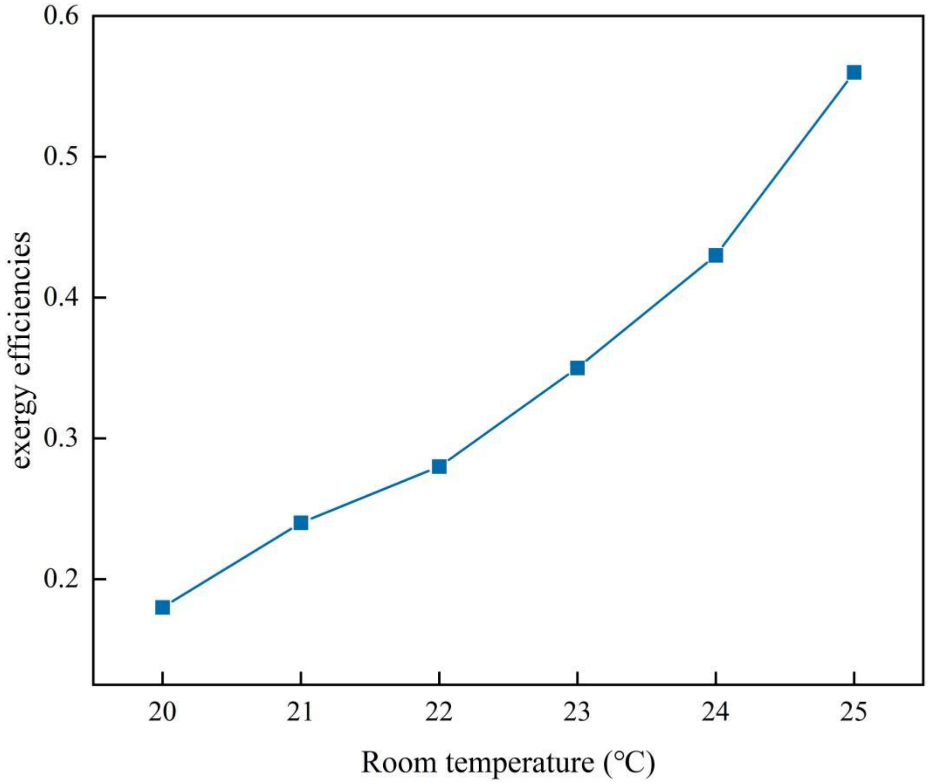


Fig 5-20Variation of exergy efficiency with room temperature

5.6.4 Analysis of systems exergy efficiency

The heat pump unit, conveying pipes, fan coils of the results of the analysis of the humidity recorded as shown in Table 5-12.

Table 5-12 Results of analysis of ground-source heat pump system

	exergy efficiency		Exergy loss rate		Loss factor	
	Winter	Summer	Winter	Summer	Winter	Summer
Heat pump units	23.74%	19.23%	83.66%	86.5%	76.27%	80.77%
Conveying pipes	92.69%	90.4%	1.9%	1.98%	7.31%	9.6%
fan coils	40.19%	38.1%	14.44%	11.52%	59.81%	61.9%

The soil source heat pump unit has the largest heat loss and the lowest heat efficiency value in both winter and summer conditions, because the unit consumes a lot of electricity during operation, thus resulting in the lowest heat efficiency. When comparing the heat pump units in winter and summer, it can be seen that the energy efficiency value in winter is greater than that in summer, so the heat production condition has higher efficiency. The highest efficiency of the conveying pipeline is due to the small temperature difference between the import and export of water in the pipeline, which leads to the smaller heat loss, and the pipeline is well insulated during the construction process, so the heat efficiency of the conveying pipeline can reach more than 90%, so the heat loss of the conveying pipeline can be ignored. Although the heat loss of the end fan coil is not as big as that of the heat pump unit, it should not be ignored. The reasons affecting the heat loss of the fan coil are the import and export temperature of the working mass and the room temperature. This is because the demonstration project has some special features. In summer, the number of fan coils at the end of the building is less and the number of days of operation is less because students are on vacation, so the energy efficiency of the system is poorer than in winter. The main line radiation efficiency refers to that in the heating and air conditioning system, the input radiation passes through the heat pump unit, is transported to the fan coil by the conveying pipeline, and is finally sent to the room, and the radiation gradually decreases during the conveying process, and finally becomes the revenue radiation sent to the users. In calculating the mainline efficiency of the heat pump, the energy-using units are regarded as connected in series, so the formula for calculating the mainline efficiency of the heat pump is:

$$\mu_e = \mu_{r,l}\mu_{e,s}\mu_{e,m}$$

Under winter conditions, the heat pump unit's efficiency is 23.74%, the heat pipe's efficiency is 92.69%, and the fan coil's efficiency is 40.19%; under summer conditions, the heat pump unit's efficiency is 19.23%, the heat pipe's efficiency is 90.4%, and the fan coil's efficiency is 38.1%. The main line heat efficiency of the soil source heat pump system is 8.85% under the heating condition, which is caused by the low heat efficiency of both the unit and the end fan coil, and the power consumption and flow rate of the heat pump unit are larger in the soil source heat pump system because the pipeline on the user side and the ground source side are more complicated. pump. The main line radiation efficiency of the system under cooling condition is 6.62%, and it is obvious that the main line radiation efficiency of the system under heating condition is higher, and this phenomenon occurs because the radiation efficiency of each energy-using unit within the system in winter condition is greater than that in summer condition, so it leads to the main line radiation efficiency of the system in winter than that in summer.

5.6.5 Comparative analysis of GSHP and other systems

Air conditioning systems have different classifications according to their different classification standards, which can be divided into all-air air conditioning systems, hot and cold water unit air conditioning systems, air-water air conditioning systems and refrigerant air conditioning systems according to different delivery media; and compressed air conditioning systems and absorption air conditioning systems according to their host types, and according to the special air climate characteristics of severe cold regions, air-cooled heat pump +Therefore, this paper selects the air-cooled heat pump + centralized heating system and the soil source heat pump system for energy efficiency analysis and comparison. The heat production condition is centralized heating, which mainly consists of heat source, heat network and heat user, and is a more widely used heating method in cities and towns at present. In this paper, we choose gas boiler as the heat source and hot water pipe network as the heat network, and deliver the high temperature hot water from the heat source to the user side through the hot water pipe network to realize the purpose of heat exchange between the user side and indoor environment. The use of centralized heating system can replace a large number of small coal-fired boilers, which can not only improve the environment, but also have lower operating costs. However, as centralized heating systems are increasingly used in cities and towns, some problems have arisen, such as scaling of circulating water when it encounters heat, and rusting of the inner walls of pipes, which can lead to a significant reduction in system efficiency and an increase in operating costs.

The formula for calculating the efficiency of the boiler's radiation is shown below:

Heat input of the gas boiler is expressed as follows:

$$E_1 = \lambda \frac{Q}{\eta_r} \tag{5-33}$$

The heat output of the gas boiler is expressed as follows:

$$E_2 = \left(1 - \frac{T_0}{T}\right) Q \tag{5-34}$$

Thermal efficiency of gas boiler output:

$$\eta_g = \eta_r \frac{(T - T_0)}{\lambda T} \tag{5-35}$$

Heat exchanger efficiency:

$$\frac{\left(1-\frac{T_0}{T_1}\right) q_2}{\left(1-\frac{T_0}{T_2}\right) q_1} = \frac{\left(1-\frac{T_0}{T_1}\right) \eta_h q_1}{\left(1-\frac{T_0}{T_2}\right) q_1} = \frac{(T_2 - T_0) T_1}{(T_1 - T_0) T_2} \eta_h \tag{5-36}$$

The calculation formula of the conveying pipeline and radiator is the same as that of the soil source heat pump, and the heat efficiency of the heating boiler is 0.39, the heat efficiency of the conveying pipeline is 0.99, the heat efficiency of the heat exchanger is 0.49, the heat efficiency of the radiator is 0.39, and the main line heat efficiency is 0.07. The energy efficiency comparison between the soil source heat pump system and the air-cooled heat pump + central heating The comparative analysis records of exergy efficiency of the system under winter working conditions are shown in Table 5-13.

Table 5-13 Comparison of exergy efficiency between two systems under heating condition

	Cooling and heating sources	Conveying pipeline	End units	Mainline exergy Efficiency
Ground source heat pump	23.74%	92.69%	40.19%	8.85%
Centralized heat supply	39%	99%	39%	7%

By comparing the ground source heat pump system of this demonstration project with the centralized heating method, it can be seen that the heat source of both is the part of the whole system that has the lowest efficiency of the barnacle. After consulting the relevant information, it is learned that the thermal efficiency of the heat source is related to the scale of the heat source, and the larger the scale of the heat source, the higher its thermal efficiency, therefore, it is beneficial to improve the barnacle efficiency of the system when a large heat source is used. At the same time, it can be seen from the heat source's heat analysis model that increasing the temperature of the heat source's import and export can also realize the improvement of the heat source unit's heat efficiency. The radiation efficiency of the conveying pipeline is the highest part of the whole system, and the difference between the radiation efficiency of fan coils and radiators is not large, but comparing the main line radiation efficiency, it can be found that the radiation efficiency of the ground source heat pump system is higher, which indicates that the energy efficiency of the ground source heat pump system is higher than that of the central heating system, and it should be worth to be promoted and used on a large scale.

The average energy efficiency of a conventional air-cooled heat pump under cooling conditions is 2.9, with an average cooling water inlet and outlet temperature of 35℃ and a chilled water inlet and outlet temperature of 9.5℃. The theoretical model of its assembly analysis is the same as that of the soil source heat pump unit, and its assembly efficiency calculation formula is shown in (5-35), and the assembly efficiency of the air-cooled heat pump unit is calculated to be 13.76%.

The air-cooled heat pump system has the same transmission piping and end fan coil equipment as the soil source heat pump system, so the results of the analysis and calculation of the RADIUM are the same as those of the soil source heat pump air conditioning system, and the results of the RADIUM analysis and calculation of the air-cooled heat pump system are summarized as shown in Table 5-14.

Table5-14 Comparison of exergy efficiency of under cooling conditions

	Cooling and heating sources	Conveying pipeline	End units	Mainline exergy Efficiency
Ground source heat pump	19.23%	90.4%	38.1%	6.62%
Air-cooled heat pumps	13.76%	93.09%	24.8%	3.18%

The comparison of the two systems in terms of the radiation analysis shows that the mainline radiation efficiency of the ground source heat pump system is greater, and the radiation efficiency of the two conveying pipes and terminal fan coils is the same, which leads to the calculation results because the radiation efficiency of the ground source heat pump unit is greater than that of the air-cooled heat pump system, and it is known from the formula of the radiation efficiency of the unit that the main factor affecting the radiation efficiency of the unit is the energy efficiency value of the unit, because the energy efficiency of the heat pump unit is The energy efficiency value of the heat pump unit is higher than that of the air-cooled heat pump system, which leads to the greater heat pump unit's efficiency. Moreover, in cold regions, air-cooled heat pumps are prone to frost, and the efficiency of the system will be affected, while ground-source heat pump system can effectively avoid the problems of air-cooled heat pump system and has better energy-saving benefits. Therefore, it can be seen from the results of the system energy saving analysis that the use of "area-compensating" not only solves the cold accumulation phenomenon in cold regions due to geothermal imbalance, but also has better energy saving benefits, and is worth promoting and applying in cold regions.

5.6.6 Optimization suggestions

The following optimization recommendations can be derived from the energy efficiency analysis and the endemic analysis of the ground source heat pump system:

1.When the system is analyzed, the heat pump unit is the part of the system with the largest heat loss, which is due to the fact that the heat and cold source is located at the beginning of the heat pump system, with more energy loss, and the unit consumes a large amount of electric power when it is working, resulting in its low heat efficiency. Through the heat pump unit's heat analysis model, we know that the factors affecting the heat pump unit's efficiency are the unit's energy efficiency value and the average temperature of chilled water and cooling water, and it is calculated that the temperature of chilled water and cooling water has less influence on the efficiency of the heat pump unit, so we say that improving the energy efficiency value of the unit is the key to improving its efficiency.

2.The efficiency of the heat pump system can reach more than 90% in the heat pipe, this is because in the design and construction stage, the heat insulation of the conveying pipeline, compared with the heat pump unit and the end fan coil, the heat loss is very small, so it can be considered that the heat loss of the conveying pipeline is negligible.

3.The end fan coil is also the part of the whole system with more heat dissipation loss. By studying the heat dissipation analysis model of the fan coil, we can see that the factors affecting the heat dissipation efficiency are mainly the import and export temperature of the working mass and the room temperature, etc. When the temperature of the working mass is closer to the room temperature, the higher the heat dissipation efficiency, i.e., the way to improve the import and export temperature of the end of the system to improve the heat dissipation efficiency of the fan coil.

4.When calculating the mainline radiation efficiency of the system, the mainline radiation efficiency of the system is 8.85% in winter conditions and 6.62% in summer conditions, while the mainline radiation efficiency of the general air conditioning system is 3%. When comparing the radiation efficiency of the soil source heat pump system with that of the conventional air-cooled heat pump + central heating system, it can be concluded that the soil source heat pump system has higher radiation efficiency.

After analyzing the energy efficiency and the data base of the demonstration project, it was found that the soil source system can solve the problem of soil heat imbalance in the cold region and bring better energy efficiency, which is worth promoting and applying.

5.7 Summary

This chapter discusses the energy efficiency of the ground source heat pump system in terms of both energy analysis and fire use analysis. The results of monitoring data for 8 years of system operation are analyzed, and the changes in operating performance after 30 years of system operation are analyzed through simulation studies. Also, the fire use analysis is performed for each energy-using unit in the system relative to the total energy use.

The first part of the study focused on confirming the long-term stable operation of the ground source heat pump system. The analysis considered factors such as supply and return water temperature variations, flow rate variations, and average input power variations between the ground source side and the user. It was found that after 8 years of operation, the system maintained a stable performance with a high attainment of the coefficient of performance (COP), indicating good energy savings.

In the second part, simulated data were used to analyze the energy efficiency of the system under different conditions. COP values were calculated for the system in winter without compensation mode, for the cooling zone with compensation mode, and for heating only. The results show that the system is still operating efficiently even after 30 years of operation, with a relatively high average COP for winter conditions.

The third section calculates the primary energy efficiency for both winter and summer conditions and shows that the ground source heat pump system has a higher energy efficiency compared to the conventional heating system. The system achieves significant energy savings of 47.9%.

Finally, the analysis focused on the efficiency of the ground-source heat pump system, specifically examining the energy-using units. It was found that the lowest efficiencies occurred at the beginning of the main energy-using lines, resulting in significant heat losses. However, the heat losses in the delivery piping were negligible and the heat loss from the delivery piping was very small. A comparison with a conventional air-cooled heat pump + central heating system shows that the soil source heat pump system is more efficient.

Overall, the study concludes that the use of area compensation technology effectively ensures the stability and energy efficiency of the ground source heat pump system in long-term operation.

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Chapter 6

ECONOMIC AND ENVIRONMENTAL ANALYSIS OF GSHPS

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6.1 Content

Ground Source Heat Pump is widely used in heating and cooling as a clean and efficient energy utilization technology. In cold regions, ground source heat pump systems have significant economic and environmental benefits. In this paper, we analyze the economic and environmental benefits of Area-compensated ground source heat pump systems in cold regions that achieve cooling and heating load balance through area compensation technology to assess their potential for sustainable development and environmental protection. The results show that the Area-compensated ground source heat pump system can operate stably and efficiently over a long period of time, and although the initial investment in the system is high, the initial investment can be recovered in a relatively short period of time by reducing energy consumption and operating costs. Compared with traditional heating and air conditioning systems, ground source heat pump systems can significantly save energy consumption and operating costs. At the same time, with the long-term operation of Area-compensated ground source heat pump systems, carbon dioxide emissions and air pollution can be greatly reduced compared to conventional systems. Area-compensated ground source heat pump systems provide a new way for sustainable development and environmental protection in cold regions by reducing energy consumption and operating costs, greenhouse gas emissions and pollutant release, and support the promotion of ground source heat pump systems in practical applications.

6.2 Introduction

Global carbon emissions have increased significantly since industrialization[1]. Since the mid-20th century, global CO2 emissions have increased exponentially, and governments and international organizations have been actively engaged in cooperation and initiatives to reduce emissions through a range of measures, including energy transition(increasing the share of renewable energy and reducing fossil fuel use), energy efficiency improvements, and promoting sustainable development[2-4] . Ground source heat pump systems(GSHPs) have great potential for sustainability and energy savings as an environmentally friendly heating and air conditioning technology[5]. GSHPs can significantly reduce greenhouse gas emissions and dependence on fossil fuels compared to traditional coal, oil or natural gas-fired systems[6, 7].

However, GSHPs may suffer from thermal imbalance under long-term operation, resulting in reduced system efficiency, energy waste and reduced comfort[8, 9]. The operation of a GSHPs results in a change in subsurface soil temperature[10]. In the heating mode, the underground heat exchanger absorbs heat energy from the soil, causing the soil temperature to decrease, while in the cooling mode, heat energy is released into the soil, causing the soil temperature to increase[11]. If the temperature in the subsurface soil drops excessively, it may lead to a decrease in the heating effect of the GSHPs. The ability of the underground heat exchanger (GHE) to absorb heat energy will be limited, thus reducing the heating performance of the system. [12] designed an optimized GHE structure to solve the subsurface soil thermal imbalance problem, and the results showed that the tree-structured GHE improved the heat transfer performance by 25.3%.[13] simulated different quantitative models to compare the effects of different factors on GSHP operational performance, and the results showed that high load operation and the distance between and smaller borehole can lead to changes in soil temperature and adversely affect GSHPs performance. In summary, the studies maintain the thermal stability of the GSHPs by changing the cooling and heating load balance [14]and optimizing the underground buried pipe spacing to enable its efficient long-term operation.

In the early stage of GSHPs application, the higher initial investment became a resistance to its development[15, 16]. However, some studies have shown that despite the high initial investment in ground source heat pump systems, they are usually able to recover their costs quickly and realize significant economic benefits in long-term operation[17-19].[20] analysis found that for a design life of 20 years, air-source heat pump (ASHP) systems are financially slightly higher than GSHPs; however, for a design life of 40 years, GSHPs provide much greater cost savings than other alternatives, including ASHP systems. [6] monitored the thermal performance of a GSHPs in a large building, showing high efficiency and significant energy savings. The economics of different heating modes were compared, with solar-coupled GSHP (SGSHP) initially being more economical, but GSHP becoming more economical in the long run. Several studies have compared the economics of GSHP systems with other systems.[21] compared the economics of GSHP with air source heat pumps in South Africa and showed that GSHP systems are more economical. An economic line analysis in the medium and long run was conducted by[22].

Due to the low carbon energy use and efficient energy use of GSHPs, it can significantly reduce greenhouse gas emissions, especially carbon dioxide[23, 24]. According to research, compared to traditional coal-fired heating systems, GSHPs can reduce greenhouse gas emissions by more than 40%[25], further reducing the negative impact on climate change[26]. In Southwest Germany, GSHPs are being installed in large numbers due to subsidy programs, and studies have found that one GSHP system reduces CO_2 by 1800-4000 kg per year, and all installed systems reduce CO_2 emissions by 2000 tons per year[1].

The object of this study is a public building-demonstration project located in Changchun, Jilin Province, a cold region in northeast China. The building type is a Class A public building with a building height of 23.9 meters and a total construction area of about 25,500 square meters, with the main functions including lecture halls laboratories, multimedia classrooms, conference rooms, etc. According to the load situation of the building, two GSHP CUWD80A5Y-HC units produced by Daikin Air Conditioning were selected for the project, with a heating capacity of 186.6kW and a cooling capacity of 211.8kW. The input power in the case of heating is 50.3kw. The evaporator flow rate is 30.6m^3 /h, the condenser flow rate is 36m^3 /h, 6 circulating water pumps, and the buried pipe Polyethylene pipe with inner diameter 25mm and outer diameter 32mm is used.

The object of this paper is a GSHPs applied to a cold region in northern China. Due to the climatic characteristics of cold regions, the heat required in winter is much greater than the cooling required in summer, and the GSHPs will have a thermal imbalance in the soil during long-term operation[27]. The underground heat exchange system uses the soil as a cooling and heating source and utilizes GHE for heat exchange[28]. The drilling area is divided into 5 sections. A total of 120 GHEs form the heat exchange system, which is buried at a depth of 100 m (Figure1). To avoid the above phenomenon, at the beginning of the design, the energy consumption simulation of the project was carried out and the annual accumulated heat in winter was calculated to be 1.350 × 107 kW h and the accumulated cooling in summer was 0.714 × 107 kW h. The ratio between the two is 1.891:1. In order to balance the heat supply in winter and summer, the project was divided into heating and cooling zones, as shown in Figure 1. The cooling area is A+B area with 14999.7m^2 and other areas are not cooled; the heating area is B area with 8386.2m^2 and A area is heated by city heat pipe network as shown in Figure 2. The ratio of cooling area to heating area is 1.789:1. By increasing the cooling area, the cooling and heating loads tend to be balanced, and the thermal compensation is made to the underground soil during the cooling season, so as to maintain the thermal balance of the underground soil[29].

6.3 Economic benefits

In Chapter 5, the energy efficiency of the ground source heat pump system has been comprehensively analyzed, but for a complete and comprehensive assessment of its adaptability, it should also be judged from the economic point of view whether the system costs less money based on energy savings, and therefore needs to be evaluated economically over its whole life cycle. Therefore, in this chapter, the advantages of the ground source heat pump system are better reflected by comparing the economic analysis of this demonstration project with the conventional air-cooled heat pump unit + central heating system.

Commonly used economic analysis methods mainly include static analysis methods and dynamic analysis methods, of which static analysis methods do not consider the impact of time on investment and return, while dynamic payback period is the change of the initial investment and operating cost of the program over time, taking into account the impact of time relative to capital. The main evaluation indexes include static payback period, return on investment, dynamic payback period, etc.

6.3.1 Initial investment and annual operating costs

In Chapter 2, the basic overview of the demonstration project has been introduced in detail, including the models of the units in the system and the basic parameters, and the two schemes are described as follows:

Option 1: Heat Pump Unit: CLIMAVENETA scroll heat pump unit.Heating Capacity: 186.6 kW.Heating Power: 50.3 kW. Cooling Capacity: 211.8 kW. Cooling Power: 39.4 kW. System Components: One circulation pump on the air conditioning side, One circulation pump on the ground source side.

Option 2: Heat Pump Unit: Air-cooled heat pump unit. Given the challenges posed by colder climates, this plan integrates an air-cooled heat pump alongside a centralized heating system. During winter, when outdoor temperatures plummet, the air-cooled heat pump's operation can be hindered. Therefore, a centralized heating system is employed. When summer arrives, the air-cooled heat pump takes the stage for cooling needs. To cater to the building's load requirements, an air-cooled heat pump with a robust 298 kW heating capacity and a substantial 268.4 kW cooling capacity was selected.

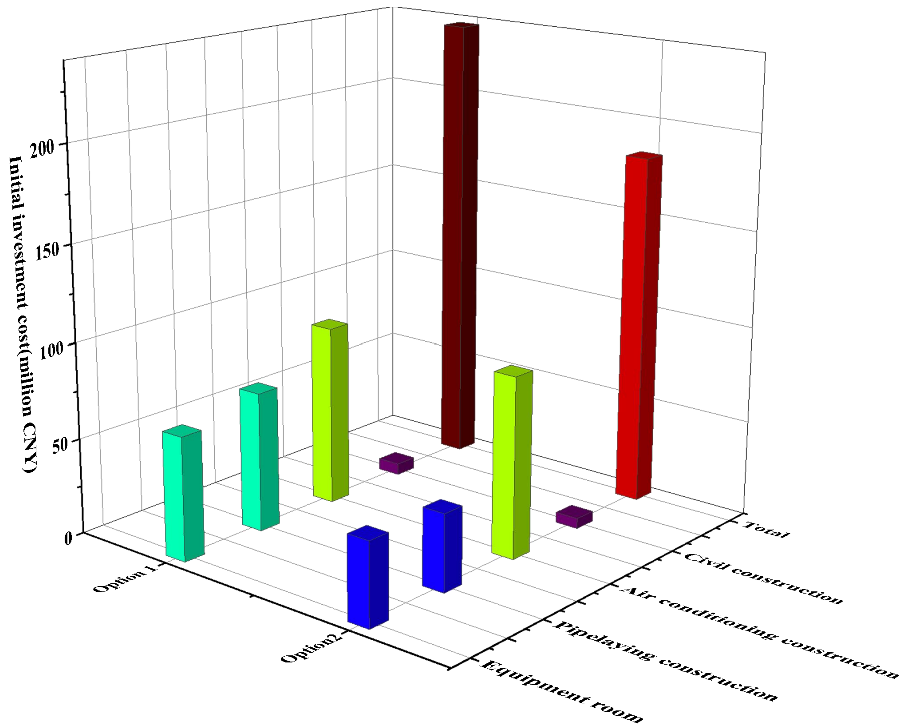

Fig 6-1 Two options for initial investment

The initial investment for this demonstration project is divided into three primary components: the plant room section, the outdoor buried pipe drilling section, and the indoor air conditioning system. Within these, the plant room component primarily encompasses installation expenses and equipment costs. The initial investment for both options is outlined in Table 6-1 as follows:

Table 6-1 Summary of initial investments in two Option

	Equipment room costs (million CNY)	Pipelaying construction costs(million CNY)	Air conditioning system engineering fees (million CNY)	Civil construction costs (million CNY)	Total (million CNY)
Option 1	64.5	72.8	92	6.2	235.5
	Equipment room costs (million CNY)	Pipelaying construction costs(million CNY)	Air conditioning system engineering fees (million CNY)	Civil construction costs (million CNY)	Total (million CNY)
Option 2	43.2	40.3	92	5.4	180.9

According to the information in Table 6-1, it's evident that Option 1's initial investment is notably higher, being 1.2 times greater than that of Option 2. This discrepancy is primarily attributed to the increased construction costs associated with drilling and pipe burial in Option 1. Consequently, when considering initial investments alone, the conventional air-cooled heat pump system of Option 2 emerges as the more cost-effective choice. However, it's important to note that relying solely on initial investment comparisons doesn't provide a comprehensive understanding. A holistic assessment should also account for the systems' entire life cycles.

The annual operating costs for the soil source heat pump system encompass multiple factors, including electricity expenses from the unit's operation, equipment maintenance costs, and caretaker salaries. Similarly, the annual operating costs for the air-cooled heat pump + central heating system comprise central heating fees, electricity costs linked to the unit's operation, and equipment maintenance expenses. For the sake of simplicity, equipment depreciation costs have been omitted.

During the winter season, referring to the conditions of 2016, the heating period spans from October 25 to April 10 of the following year, encompassing 169 days. In the subsequent summer season, based on the conditions of 2017, the cooling period ranges from June 23 to September 10, spanning 95 days.

For Option 1 in winter: The monitoring system observed the consumption of 88,552 kWh of electricity during operation. With an assumed electricity price of 0.932 Yuan/kWh in the Changchun area, the winter electricity cost sums up to 83,000 Yuan. Additionally, the soil source heat pump system requires specialized personnel for management and routine maintenance after becoming operational. This entails two maintenance personnel with a monthly salary of 1,800 Yuan each, totaling 14,400 Yuan over the 4-month winter operation. A winter maintenance cost of 650,000 Yuan is also incurred, yielding a combined total of 113,900 Yuan for the winter season.

For Option 1 in summer: The system consumes 42,338 kWh of electricity during operation, amounting to an electricity cost of 39,500 Yuan. Labor costs are calculated at 720,000 Yuan for the summer period, while no maintenance costs are recorded for the summer of 2017. The total operating cost for the summer period is 586,000 Yuan. A comprehensive summary of the annual operating costs is presented in Table 6-2.

Table 6-2 Summary of annual operating costs of heat pump systems

	Electricity (million CNY)	Labor cost (million CNY)	Maintenance fee (million CNY)	consider (million CNY)	Total (million CNY)
Heating conditions	8.35	1.47	0.68	11.5	16.16
Cooling conditions	3.93	0.73	_	4.66	

Option 2: The winter working condition is heated by centralized heating for the project, and the centralized heating cost for winter heating is calculated at 27 RMB/m^2. The total heating cost is 135,000 yuan. When centralized heating is used, there is no need to arrange maintenance workers, so the maintenance cost is negligible. The electric energy consumed by the air-cooled heat pump for summer cooling is taken as 14.4 yuan/m^2, with a cooling area of 10,000m2, totaling 144,000 yuan. The maintenance cost of the air-cooled heat pump system is less and can also be neglected. The total annual operating cost of program two is 279,000 yuan. The initial investment

and annual operating costs of the two options are summarized as shown in Table 6-3.

Table 6-3 Comparison of initial investment and annual operating costs between the two options

	Initial Investment (million CNY)	Annual Operating Costs (million CNY)
Ground source heat pump system	235.5	16.16
Air-cooled heat pump + central heating system	180.9	27.9

Upon evaluating the annual operating costs of the two systems, a significant disparity emerges: the annual operating cost of the air-cooled heat pump + central heating system is 1.85 times greater than that of the soil source heat pump system. This comparison underscores the economic advantage of the soil source heat pump system, primarily attributed to the distinct heating and cooling sources employed by each system. The soil source heat pump system's design ensures efficient operation, contributing to its cost-effectiveness.

However, a more nuanced analysis is necessary since the high initial investment of the heat pump system complicates the comparison between the two methods. Solely considering initial investment and operating costs is insufficient to determine which approach is more economically viable. As a result, the next step will involve a comprehensive economic assessment of both solutions, based on economic evaluation indices.

6.3.2 Simple payback period and ROI

In the preceding section, we computed the initial investment and yearly operating expenses for both the soil source heat pump system and the air-cooled heat pump system. By assessing the demonstration project's initial investment, we laid the groundwork for subsequent analysis. The upcoming section will delve into the comparison with the air-cooled heat pump system, where we will calculate and scrutinize the present value of costs, the annualized cost, and the payback period for both systems.

The simple payback period is the net return of the annual operating costs of the two programs to recover the years consumed by their incremental initial investment without considering the time value of money, and in the calculation, the project is put into use when it is completed, and the time of use is used as the starting time, the shorter the simple payback period, the faster the return effect and the more economical the program is, and its calculation formula is shown in (6-1).

$$n = \frac{\Delta C}{\Delta N} = \frac{235.5-180.9}{27.9-16.16} = 4.6 \qquad (6\text{-}1)$$

Where, ΔC is Difference between the initial investment of the two solutions; ΔN is Difference in annual operating costs between the two options.

After thorough calculations, it has been determined that the soil source heat pump system exhibits an initial investment recovery period of 4.6 years in comparison to the air-cooled heat pump system. Typically, the principal system of the soil source heat pump configuration maintains a service life of 20 years, while the subterranean buried pipe component is designed to endure for 50 years. In contrast, the air-cooled heat pump system carries a 20-year service life. Despite its higher initial investment, the cumulative expenses associated with the air-cooled heat pump system surpass those of the soil source heat pump system after 4.6 years of active system operation. As a result, it is confidently asserted that the soil source heat pump system proves more economically viable than the air-cooled heat pump + central heating system.

The return on investment is mainly the ratio of the revenue obtained after the investment to the cost time required[30]. For soil source heat pump system, the return on investment is the ratio of the annual energy cost savings to the initial investment increase, that is, the inverse of the simple payback period, see formula (6-2), the calculation method is simple and easy to calculate.

$$R_1 = \frac{1}{n} \times 100\% = \frac{1}{4.6} = 21.7\% \quad (6\text{-}2)$$

Where R_1 is ROI.

6.3.3 Present value of costs and annual value of costs

The present value of cost mainly refers to the conversion of the initial investment and annual operating costs of the system into the sum of its cash equivalent[31], which is calculated as shown in (6-3), and the smaller the present value of cost, the better the economy of the system[32].

$$P_C = C + N(P/A, i_0, n) \quad (6\text{-}3)$$

Where Pc is present value of the cost of the system, million dollars; C is initial investment, million dollars; N is annual operating costs, million dollars; $(P/A,i_0,n)$ is annual cash value coefficient.

The benchmark rate of return for both systems i_0 is taken as 10%, the service life of both units is generally about 20 years, and n is 20, so it is found that (P/A,i0,n) = 8.5 The present value of the cost of the two systems is calculated as follows:

Ground source heat pump system: Pc=237.3+8.5 × 15.06=365.36 (million yuan) (6-4)

Air-cooled heat pump + central heating system: Pc=182.7+8.5×27.9=419.85 (million yuan) (6-5)

The annual value of the cost refers to the conversion of the initial investment of the system into an equal amount per year, which can comprehensively reflect the utilization of the initial investment and annual operating costs, and is one of the economic evaluation indicators, similar to the present value of the cost, the smaller the annual value of the cost, the better the economy of the system, and its calculation formula is shown in (6-6).

$$A_C = P_C(A/P, i_0, n) \quad (6\text{-}6)$$

where: Ac - the annual value of the cost of the system, million dollars; (A/P,i0,n) - the capital recovery factor.

The present value of cost and annual value of cost for the two scenarios are summarized in Table 6-4.

Table 6-4 Comparison of present and annual cost values of two options

	Present value of costs	Annual value of fees
Ground source heat pump	372.86	43.86

Air-cooled heat pump + central heating system	418.05	49.18

6.3.4 Dynamic payback period

The dynamic payback period is the time required for the annual revenue value to recover its total initial investment, also known as the investment payback period. For this system, its dynamic payback period refers to the annual operating cost savings to offset the initial investment cost of the system construction required years, although its calculation method is complex, but it overcomes the shortcomings of the static analysis method, and can correctly reflect the capital recovery time. Its calculation formula is shown in (6-7).

$$\sum_{t=0}^{P}(CO - CI)(1+i)^{-t} = 0 \tag{6-7}$$

Where: P is dynamic payback period; CO is cash outflow; CI is cash inflow; i is benchmark rate of return, taken as 3%.

Based on the calculation provided, the dynamic payback period is a measure of the time required for the annual revenue value to recover the total initial investment[33]. It takes into account the difference in initial investment between the two systems as the cost increment and the difference in annual operating costs as the revenue. The dynamic payback period is calculated as follows:

When t = 0, CI = 0, CO = 235.5 - 180.9 = 54.6 (million) (6-8)

When t = 1..., CO = 0, CI = 27.9 - 16.16 = 11.74 (million) (6-9)

From Equation (6-7), the dynamic payback period of this demonstration project system is 4.7 years, thus indicating that the payback period of the system is 4.6 years when the time value of capital is not considered and 4.8 years when the time value of capital is considered.

6.3.5 Economic benefits of coal saving volume

The Evaluation Standard for Renewable Energy Building Application Project points out that when using ground source heat pump system, the electrical energy generated during the operation of the system can be converted into standard coal so as to compare with the traditional boiler heating method, and the heat source of the ground source heat pump system is geothermal energy, which is two kinds of renewable energy, and has lower environmental impact than the traditional boiler heating method. In Chapter 5, the formula for the amount of conventional energy substitution is given, and the total system coal savings are calculated based on the data from eight years of system operation as shown in Table 6-5.

Table 6-5 System coal saving

Running time (year)	Winter Energy saving (tons of standard coal)	Summer Energy saving (tons of standard coal)	Annual energy saving (tons of standard coal)
2013	50.96	0	50.96
2014	50.22	35.13	85.35
2015	45.45	36.54	81.99
2016	48.54	35.85	84.39

2017	50.65	36.72	87.37
2018	47.88	34.98	82.86
2019	48.36	35.47	83.83
2020	46.72	36.11	82.83

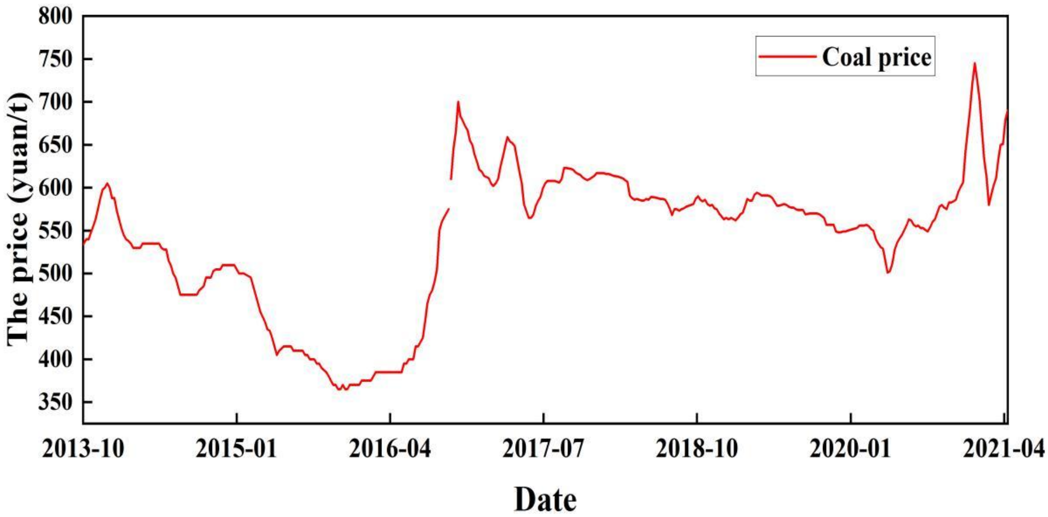

Fig 6-2 Thermal coal prices in China

Table 6-5 Coal cost savings

Running time (winter)	Average thermal coal price (CNY/t)	Total amount (CNY)	Running time (summer)	Average thermal coal price (CNY/t)	Total amount (CNY)
2013	554	28232	2013	—	—
2014	489	24558	2014	482	16933
2015	375	17044	2015	401	14653
2016	638	30969	2016	462	16563
2017	611	30947	2017	589	21628
2018	578	27675	2018	578	20218
2019	552	26695	2019	577	20466
2020	626	29247	2020	556	20077

It can be seen from the table that the system has been in long-term operation for 8 years. Compared with the conventional boiler room heating energy saving 388.78tons of standard coal, compared with the conventional air conditioning refrigeration energy saving 250.8tons of standard coal, the system has been running for 8 years a total of 639.58 tons of standard coal of energy saving effect. According to the average price of thermal coal in previous years, as shown in Figure 6, the cost of thermal coal saved in winter working condition was 215367CNY and that in summer working condition was 130,538CNY, totaling: 345,905CNY. This shows that the GSHP can reduce a large amount of coal energy in the long-term operation[34]. The popularization of GSHP in cold areas can accelerate the adjustment of China's coal-based energy structure, and has a high popularization and use value.

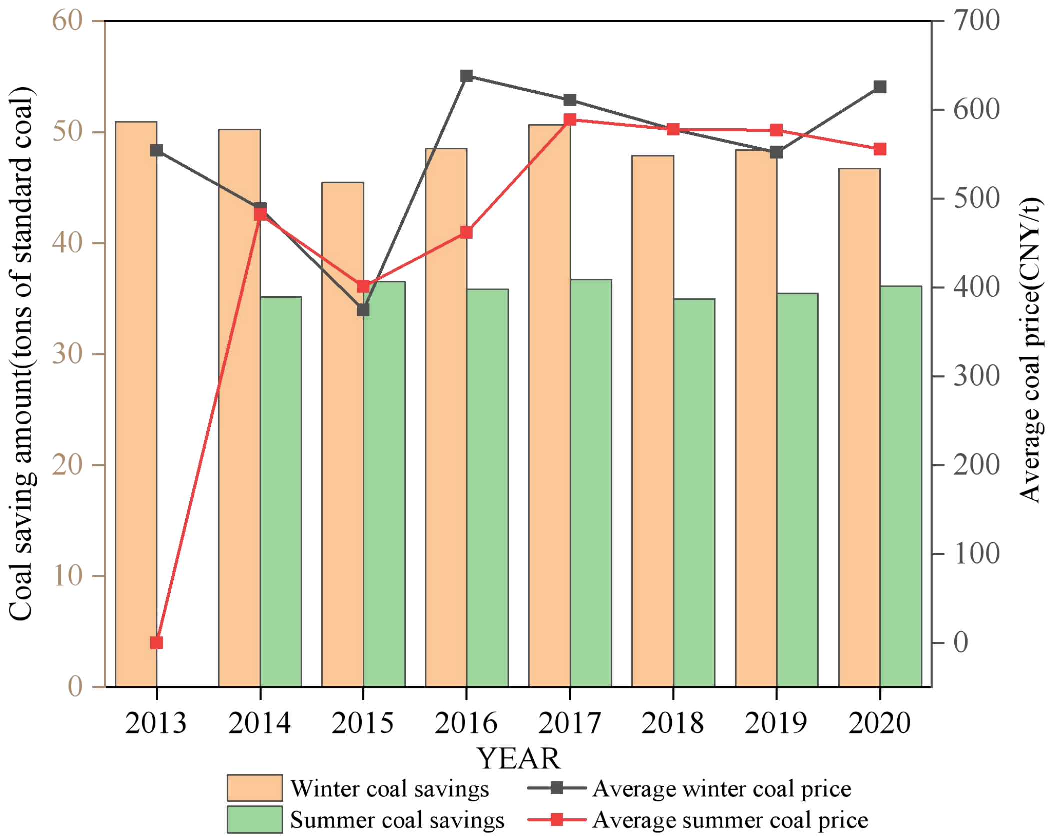

Fig 6-3 Coal saving volume and coal price

6.4 Environmental benefits

The Evaluation Standard for Renewable Energy Building Application Project points out that when GSHPs is used, the electrical energy generated during the operation of the system can be converted into standard coal and thus compared with the traditional boiler heating method[35]. According to the relevant provisions of the "Guidelines for the Measurement and Evaluation of Renewable Energy Building Application Demonstration Projects" for the detection of environmental benefits, the emission reduction of carbon dioxide, sulfur dioxide and soot can be calculated by the following formula[6]:

CO2 emission reduction Equation:

$$Q_{CO_2} = 2.47Q_{\mathrm{bm}} \tag{6-8}$$

SO2 emission reduction Equation:

$$Q_{SO_2} = 0.02Q_{\mathrm{bm}} \tag{6-9}$$

Soot emission reduction Equation:

$$Q_{\mathrm{Soot}} = 0.01Q_{\mathrm{bm}} \tag{6-10}$$

where: QCO_2 is carbon dioxide emission reduction, t/a; QSO2 is Sulfur dioxide emission reduction t/a; Q_{Soot} is Soot emission reduction t/a; Q_{bm} is standard coal saving, t/a; 2.47 is carbon dioxide emission factor of standard coal, dimensionless; 0.02 is sulfur dioxide emission factor of standard coal, dimensionless; 0.01 is standard coal soot emission factor, dimensionless.

According to the calculation of energy saving, as shown in Table 6-6, the cumulative CO_2 emission reduction of the system in 8 years of operation is 1579.75t, SO_2 emission reduction of 12.79t, and soot emission reduction of 6.39t. This shows that the GSHP can reduce a large amount of coal energy and CO_2 and other harmful substances emissions in the long-term operation[34].

Table 6-6 Pollutant reduction in GSHPs

Running time (year)	Annual CO_2 reduction (t)	Annual SO_2 reduction (t)	Annual Soot reduction (t)
2013	125.87	1.0192	0.5096
2014	210.81	1.707	0.8535
2015	202.51	1.6398	0.8199
2016	208.44	1.6878	0.8439
2017	215.81	1.7474	0.8737
2018	204.66	1.6572	0.8286
2019	207.06	1.6766	0.8383
2020	204.59	1.6566	0.8283

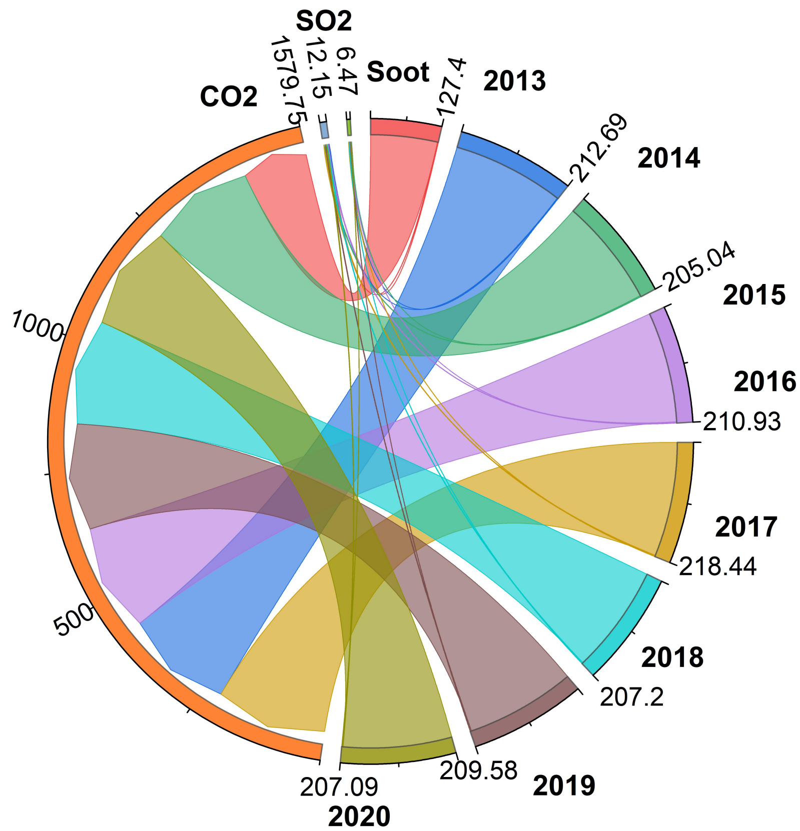

Fig 6-4 Emissions of pollutants for each year

6.5 Analysis of the suitability of GSHP

In China, there are no established norms and standards for evaluating the suitability of soil source heat pumps. However, the industry commonly refers to the standard DZ/T0225-2009 and the shallow geothermal energy survey and evaluation specification for guidance. According to these guidelines, the soil within the designated regions is classified into the Fourth Series and the Chalk Series. The Fourth Series soil is considered suitable for constructing soil source heat pump systems, while the Chalk Series contains more mudstone and sand conglomerate, making the drilling process more challenging. The thermal conductivity of rock and soil is influenced by factors like water content and density. Generally, denser rocks have higher thermal conductivity compared to loose rocks. Practical applications have shown that the thermal conductivity of specific rocks or minerals is not crucial for designing soil source heat exchange systems. Through field surveys and thermal response tests, it was determined that the heat exchange per linear meter of the test heat exchange hole was 25W/m, and the comprehensive heat transfer coefficient of the soil was 2.573W/(m K). These findings were compared with the evaluation system developed by Wang Nan from Jilin University for assessing the suitability of shallow geothermal energy development in the Changchun area. Based on this comparison, the geological conditions in question were found to be suitable for implementing a GSHPs.

It's important to note that the evaluation of GSHPs should also consider factors beyond geological conditions. Factors such as energy demand, installation costs, ongoing maintenance requirements, local regulations, climate conditions, and available incentives or subsidies should all be taken into account to determine the overall suitability of GSHPs in a specific region.

Table 6-7 Reference values of thermal conductivity of common rocks in Changchun area

Rock type	Thermal conductivity W/(m • ℃)	Rock type	Thermal conductivity W/(m • ℃)
Water-bearing soil	0.82—2.18	Sandstone	1.55—3.46
Dry sand	0.18—0.36	Shale	0.98—2.82
Wet sand	1.09—2.18	Conglomerate	1.52—2.87
Dry clay	0.27—0.45	Basalt	1.82—4.46
Wet clay	0.64—1.27	Granite	2.64—3.82
Coal	0.83—1.53	Granite amphibole	2.69—3.55

Table 6-8 Soil source heat pump system suitability zoning

Suitability level	Geotechnical structure and characteristics
More suitable	Sand layer, clay, etc., the thickness of the quaternary overburden is deep and the heat exchange capacity is good
Suitable	Fine sand, fine sand and gravel layer with medium heat transfer capacity
Unsuitable	Single gravel or bedrock, difficult construction, high cost, poor heat transfer capacity

The suitability of soil source heat pumps is analyzed based on their energy-saving benefits. When compared to conventional boiler room heating, the soil source heat pump system saves 388.78 tons of standard coal. Similarly, compared to conventional air conditioning refrigeration, it saves 250.8 tons of standard coal. Over an 8-year period, the cumulative energy-saving effect of the system amounts to 639.58 tons of standard coal.

The Jilin Provincial Library in Jilin Province represents the largest soil source heat pump project in the area. This system effectively meets the heating needs of a nearly 60,000 square meter facility, resulting in savings of approximately 1,000 tons of standard coal during a single heating season. Moreover, in Changchun, ground source heat pump systems are utilized for heating an area of 105,000 square meters. The entire ground source heat pump heating area in Changchun has reached 1,051,000 square meters, leading to energy savings of 18,000 tons of standard coal during a single winter.

Based on energy-saving calculations, the 8-year operation of the system has resulted in a cumulative reduction of 1,579.75 tons of CO2 emissions, 12.79 tons of SO2 emissions, and 6.39 tons of soot emissions. This clearly demonstrates the ability of soil source heat pumps to significantly reduce coal energy consumption and mitigate the release of harmful substances, such as CO2, over the long term.

When compared to conventional cooling and heating sources, the soil source heat pump system delivers total cost savings exceeding 345,905 CNY. While the initial investment for the soil source heat pump system is higher, its annual operating costs are lower than those of air-cooled heat pump systems. After 4.3 years of operation, the total cost of the air-cooled heat pump system surpasses that of the soil source heat pump system, making the latter a more economically favorable option. The present value and annual value of costs for the soil source heat pump system are lower, and its dynamic payback period is 4.8 years. This means that the additional cost of the system is recouped after 4.8 years of operation.

The use of soil source heat pumps has a significant impact on conserving primary energy and reducing greenhouse gas emissions, as well as addressing issues like haze and other environmental pollutants. Through long-term monitoring of a soil source heat pump demonstration project in the Changchun area, it has been determined that the soil source heat pump system is suitable for cold regions. After nearly 8 years of monitoring and analysis, the system has demonstrated stable operation, with unit energy efficiency ratios and system energy efficiency ratios surpassing national energy-saving standards. Although there may be challenges related to heat and cold load imbalances causing soil thermal imbalances, measurements of changes in the soil temperature field have confirmed that "area thermal compensation technology" effectively addresses this issue through regulation of heating and cooling areas.

Ground-source heat pumps have gained recognition worldwide as a sustainable and efficient heating and cooling technology. Evaluating their suitability in China's northern regions, including Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia Autonomous Region, Liaoning, Jilin, Heilongjiang, Shandong, Henan, Shaanxi, Gansu, Qinghai, Ningxia Hui Autonomous Region, and Xinjiang Uygur Autonomous Region, can be done by considering the resource conditions, energy-saving benefits, economic benefits, and environmental benefits. Let's examine each aspect:

Resource Conditions:

The suitability of soil source heat pumps relies on the availability of adequate ground heat resources. China's northern regions have favorable resource conditions for soil source heat pumps. The ground temperature remains relatively stable throughout the year, providing a consistent heat source for the pumps. Therefore, in terms of resource conditions, soil source heat pumps are generally well-suited to these regions.

Energy-saving Benefits:

Soil source heat pumps are known for their high energy efficiency. They extract heat from the ground during winter and transfer it indoors for heating purposes. In the summer, they can reverse the process to provide cooling. Compared to traditional boiler systems burning fossil fuels, soil source heat pumps can achieve significant energy savings. By utilizing renewable geothermal energy, they can reduce the reliance on conventional fuels and contribute to energy conservation.

Economic Benefits:

Although the upfront installation costs of soil source heat pumps are higher than traditional heating systems, they can offer long-term economic benefits. The operational costs of heat pumps are typically lower due to their high energy efficiency. With the rising costs of fossil fuels, the use of soil source heat pumps can provide cost savings over their lifespan. Additionally, as the technology matures and becomes more widespread, the cost of installation is likely to decrease, further enhancing the economic viability of these systems.

Environmental Benefits:

The adoption of soil source heat pumps can bring significant environmental benefits. As China aims to reduce pollution and greenhouse gas emissions, transitioning from conventional fossil fuel-based heating systems to more sustainable alternatives is crucial. Soil source heat pumps produce fewer greenhouse gas emissions compared to conventional boilers, as they utilize renewable geothermal energy. By reducing the reliance on coal consumption for heating, soil source heat pumps can contribute to improved air quality and a cleaner environment.

In conclusion, considering the resource conditions, energy-saving benefits, economic benefits, and environmental benefits, soil source heat pumps are generally well-suited to China's northern regions. Their adoption can help save energy, reduce greenhouse gas emissions, improve air quality, and contribute to a more sustainable heating solution. However, it is important to consider factors such as initial investment costs, infrastructure requirements, and government support for promoting renewable energy technologies when evaluating the overall suitability and feasibility of soil source heat pumps in specific regions.

6.6 Summary

In this chapter, the adaptability of ground source heat pumps in severe cold regions will be analyzed in terms of both environmental and economic benefits, and the results are as follows.

Firstly, in terms of economic analysis, static and dynamic analysis methods are used to analyze the soil source heat pump system and conventional air-cooled heat pump + central heating system, including simple payback period, return on investment, present value of cost, annual value of cost and dynamic payback period. The conclusion shows that: the initial investment of the soil source heat pump system is higher, but the annual operating cost is lower than that of the air-cooled heat pump system; when the system is operated for 4.6 years, the total cost of the air-cooled heat pump system is higher than that of the soil source heat pump system, thus it seems that the soil source heat pump system is very economical; and the present value of cost and annual value of cost of the soil source heat pump system are lower; its dynamic payback period is 4.8 years, i.e. The incremental cost can be recovered after 4.7 years.

Secondly, from the data of the system's long-term operation for 8 years, it is calculated that compared with the conventional boiler room heating energy saving of 388.78 tons of standard coal, and compared with the conventional air conditioning and cooling energy saving of 250.8 tons of standard coal, the system achieves a total energy saving of 639.58 tons of standard coal in 8 years of operation. According to the average price of coal in previous years, the cost of coal saved in winter working condition is RMB 215,367, and the cost of coal saved in summer working condition is RMB 130,538, and the total saving is RMB 345,905.

Finally, according to the calculation, the system has been operating for 8 years, the cumulative reduction of carbon dioxide emission is 1579.75 tons, sulfur dioxide emission is 12.79 tons and soot emission is 6.39 tons, which shows that GSHP can reduce a large amount of coal energy and emission of harmful substances such as carbon dioxide in long-term operation.

In summary, the ground source heat pump system is more economical and environmentally friendly compared with traditional heating and air conditioning. It is suitable for cold regions with high heat exchange rate of geotechnical structures. Therefore, it is of high significance to promote the use of ground source heat pump system in cold regions, which is conducive to changing the traditional energy structure of China and reducing the use of energy sources such as coal.

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Chapter 7

CONCLUSION AND PROSPECT

Contents

Chapter 7:

CONCLUSION AND PROSPECT 1

7.1 Conclusion 1

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7.1 Conclusion

This paper provides a comprehensive overview of the applicability of ground source heat pumps (GSHPs) in cold regions. Various aspects related to GSHPs are discussed, including addressing the challenges associated with soil thermal imbalance and optimizing heat transfer bore spacing. The paper also highlights the energy efficiency, economic and environmental benefits of GSHPs.

The main works and results can be summarized as follows:

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE, introduces the background and purpose of the study. First, the current status of global and Chinese energy applications is introduced. Secondly, the current status of building energy in China and the current measures for using alternative energy sources are presented. Third, the current development status of geothermal energy as well as ground source heat pumps is introduced, and the Chinese government's policy of vigorously developing geothermal energy and the application of ground source heat pumps in China are presented. Finally, the research objectives and logical framework of this study are summarized.

In Chapter 2, LITERATURE REVIEW ON GROUND SOURCE HEAT PUMP SYSTEMS, The types of GSHP as well as the working principle and composition are introduced, and the current status of the application and development of ground source heat pumps in previous studies, the development process of the technology and its advantages are reviewed, while the problems and technical bottlenecks encountered in the application of the technology and the problems encountered in the application for cold regions are analyzed in the context of previous studies. The literature review is conducted for the most concerned heat balance problem and energy efficiency in cold regions, and the previous research methods and conclusions are introduced.

In Chapter 3, RESEARCH SUBJECTS AND METHODS, the basic situation of the research topic, various parameters of the building and the composition and various parameters of the ground source heat pump are introduced, as well as the working principle of the ground source heat pump using area compensation technology to achieve the cooling and heating load balance of the research topic. Secondly, we introduced the application scope and method of soil temperature field modeling using CFD software to study the changes of soil temperature field during the long-term operation of the ground source heat pump system. Finally, the simulation method for ground source heat pump system performance study is introduced, and the use of TRNSYS software is described to establish the system operation performance model and the modules used in the model are explained in detail.

In Chapter 4, STUDY OF SOIL HEAT BALANCE OF GSHPS, Combined with the monitoring platform, the monitoring data of unit performance and subsurface soil temperature were studied and analyzed. Meanwhile, CFD software was used to simulate the effect of heat exchange holes on subsurface soil temperature under different spacing conditions after 30 years of system operation, and the optimization of heat exchange hole spacing in cold regions was proposed. This study provides first-hand real-time monitoring data of GSHP operation in cold regions, as well as temperature field variation data of subsurface soil at different depths for 8 consecutive years. The results show that the ground-source heat pump system maintains the thermal balance of subsurface soil temperature by regulating the equalization of cold and heat loads in the severe cold region. The practicality of ground source heat pumps in severe cold regions is further confirmed by simulation and experimental studies. Meanwhile, by analyzing the changes of soil temperature around the buried tube heat exchange well set with different heat exchange hole spacing, it is found that the difference of each spacing is small after long-term operation, so it is not necessary to pursue excessively to increase the heat exchange hole spacing to maintain the thermal balance of soil temperature field under the limited area of ground source heat pump project.

In Chapter 5, ENERGY EFFICIENCY ANALYSIS OF GSHPs, The energy efficiency of the ground source heat pump system is discussed in terms of both energy analysis and fire use analysis. The results of monitoring data for 8 years of system operation are analyzed, and the changes in the operational performance of the system after 30 years of operation are analyzed through simulation studies. Also, a fire analysis was performed for each energy-using unit in the system relative to the total energy use. The first part of the study focused on confirming the long-term stable operation of the ground source heat pump system. This analysis considered factors such as supply and return water temperature variations, flow rate variations, and average input power variations between the ground source side and the consumer. It was found that after 8 years of operation, the system maintained a stable performance with a high coefficient of performance (COP), indicating good energy savings. Even after 30 years of simulated operation, the system continued to operate efficiently. The primary energy efficiency was also calculated for both winter and summer conditions and showed that the ground source heat pump system has a higher energy efficiency compared to the conventional heating system. The system achieves a significant energy saving of 47.9%. Finally, the efficiency of the ground source heat pump system was analyzed, specifically examining the energy-using units. It was found that the lowest efficiencies occurred at the beginning of the main energy-using lines, resulting in significant heat losses. A comparison with a conventional air-cooled heat pump + central heating system shows that the soil source heat pump system is more efficient. Overall, the use of area compensation techniques effectively ensures the stability and energy efficiency of ground source heat pump systems in long-term operation.

In Chapter 6, ANALYSIS OF THE ECONOMIC AND ENVIRONMENTAL BENEFITS OF GSHPS, The adaptability of ground source heat pump in severe cold regions was analyzed in terms of both environmental and economic benefits. In terms of economic analysis, static and dynamic analysis methods were used to analyze the soil source heat pump system and conventional air-cooled heat pump + central heating system, including simple payback period, return on investment, present value of cost, annual value of cost and dynamic payback period. The results show that the soil source heat pump system is very economical; moreover, the present value of cost and annual value of cost of the soil source heat pump system are relatively low; its dynamic payback period is 4.8 years, i.e., the incremental cost can be recovered after 4.8 years. In terms of coal saving, calculated from the data of the system's long-term operation for 8 years, compared with the energy saving of 388.78 tons of standard coal for conventional boiler room heating and 250.8 tons of standard coal for conventional air conditioning and cooling, the system achieves a total energy saving of 639.58 tons of standard coal for 8 years of operation. In terms of environmental benefits, the system has been operating for 8 years and has reduced carbon dioxide emission by 1579.75 tons, sulfur dioxide emission by 12.79 tons and soot emission by 6.39 tons, which shows that GSHP can reduce a large amount of coal energy and emission of harmful substances such as carbon dioxide in long-term operation. Therefore, it is important to promote the use of ground source heat pump system in cold regions, which is conducive to changing the traditional energy structure of China and reducing the use of energy sources such as coal.

In Chapter 7, CONCLUSION AND PROSPECT, a critical summary of each chapter was concluded.

In cold regions, GSHPs face challenges related to soil thermal imbalance. This refers to the fact that the soil around heat exchange pipes may freeze in winter, which may reduce the efficiency and performance of the system. This paper may explore strategies and techniques that can be used to overcome this problem and maintain the optimal functionality of GSHPs in cold climates. Optimization of drilled hole spacing is another important aspect discussed in this paper. The spacing between drilled holes affects the overall heat transfer efficiency of the system. By exploring the optimal spacing, a significant amount of land area is thus saved and construction costs are reduced.

In addition, this paper highlights the energy, economic, and environmental benefits of GSHPs. GSHPs are designed to automatically adjust their operation based on prevailing conditions, such as soil temperature and load demand. This adaptability allows GSHPs to optimize their performance, reduce energy consumption, and lower operating costs. In addition, the environmental benefits of GSHPs, such as reduced greenhouse gas emissions and dependence on fossil fuels, contribute to sustainable development and environmental protection.

Overall, this paper provides a comprehensive overview of the applicability of GSHPs in cold regions, addresses the challenges associated with soil thermal imbalances, explores the optimization of heat transfer pore spacing, and highlights the energy, economic, and environmental benefits of GSHPs. The findings and insights of this paper contribute to the knowledge and understanding of GSHP technology and its potential for sustainable development and environmental protection in cold regions.

7.2 Prospect

Further research and development of technologies: Further research and development of technologies applicable to GSHP systems in cold regions should be conducted. In particular, methods to address the challenges of soil thermal imbalance need to be further explored to ensure the efficiency and reliability of the system in cold environments.

Optimize design and layout: For the heat exchange hole spacing in GSHP systems, the design should be optimized to improve the heat transfer efficiency of the system. Researchers should consider the effects of different factors, such as soil thermal conductivity and pore spacing, on system performance to determine the optimal layout and configuration.

Promote GSHP systems: GSHPs have automatic adjustment to optimize operation based on environmental conditions and load demand. Such systems can improve energy efficiency and reduce operating costs. The government and relevant stakeholders can promote the application of

GSHP systems through policy support and incentives.

Strengthen the integration of technology and policy: The integration of technology and policy is key to promoting the effective use of GSHP systems in sustainable development and environmental protection in cold regions. Governments and research institutions should strengthen cooperation, develop long-term strategies, and provide technical support and policy guidance to promote the development and application of GSHP technologies.

These outlooks and recommendations are intended to promote the sustainable development of GSHP technologies in cold regions and provide solutions for environmental protection. Through further research, technological innovation and policy support, GSHP systems can be widely used in cold regions and contribute to energy conservation and environmental protection.