博士論文

RESEARCH ON OPTIMIZATION OF MULTI-LAYER WALL THERMAL PERFORMANCE WITH PHASE CHANGE MATERIALS (PCMs)

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ABSTRACT

With the continuous improvement of living standard and indoor comfort, the building energy consumption is growing very quickly and improving building energy efficiency has been very urgent. Energy storage can reduce the time or rate mismatch between energy supply and demand. Compared with the sensible heat storage system, the phase change material (PCM) as latent heat storage becomes popular due to its higher energy storage density and a smaller masses and volumes of material. One of the potential applications for PCM in buildings is energy conservation by incorporating them in walls. It can decrease overall energy consumption by decreasing the air-conditioning cooling or heating load during summer and winter season. In addition, a time shift in peak load during the day can be achieved.

In this thesis, firstly, basic concept and research statue of PCM in buildings in Japan and China have been investigated. Then the determination method of the PCM phase-change temperature range suitable for multi- layer walls with PCMs is researched based on the theory analysis of heat transfer laws and the calculation equations is obtained. Meanwhile, the factors influencing PCM phase-change temperature range such as wall structures, outdoor thermal environment and PCM thermal physical properties are analyzed qualitatively. After that, in order to verify the accuracy of the theory calculation method, heat transfer model of enthalpy-porosity model is built and verified by published data and experiment data. Then the enthalpy porosity model is used for making verification on the PCM phase-change range obtained according theory calculation method under the different design periods of phase-change occurrence, the different location of the PCM layer and different structure of the multi-wall. At last, cases study on energy conservation of walls integrated with PCMs layer in China and Japan are done.

In Chapter 1, BACKGROUND AND PURPOSE OF THE STUDY, the worldwide energy consumption and building energy consumption situation are investigated. Then the thermal energy storage technologies are introduced. By analysis, the advantages of PCM in buildings is recognized. In addition, characteristics and the present research status of PCM in buildings including experimental and numerical study on application of PCM in building envelopes are reviewed and the purpose of this research was proposed.

In chapter 2, INVESTIGATION ON BASIC PROPERTIES OF PCM IN BUILDINGS AND RESEARCH STATUS IN JAPAN AND CHINA. Firstly, the basic properties of PCMs such as characteristics, selection criteria for the PCM suitable to building envelopes, incorporation methods of PCM into building wall are introduced. The development of PCM application in building walls are investigated. Then the research status of PCMs in buildings in Japan and China have been investigated.

In chapter 3, THEORY CALCULATION METHOD FOR CONFIRMING PCM PHASE CHANGE RANGE. According the rule of PCM phase change in building walls, principle of PCM phase change range is proposed. Then based on the theory analysis of heat transfer laws, the calculation equations of phase-change range of PCMs in multi-layer wall are got and limitations are given. Then according calculation equation, factors including outdoor temperature and wall structure influencing the range have been analyzed qualitatively. Result shows that with the increasing of summer outdoor temperature and fluctuation, liquids temperature of PCMs layer increases linearly. The moving of PCM from wall inner to outer surface leads to the whole phase change range decrease. The nearer PCM layer to wall inner surface, the lower liquidus temperature, higher solidus temperature and smaller phase change slope. The increase of thickness of wall sintered brick layer is helpful for solidus temperature increase and liquidus temperature decrease. The heat conductivity coefficient of wall sintered brick layer helps the PCM phase change range increases.

In Chapter 4, VERIFICATION ON THE CALCULATION METHOD OF PCM PHASE CHANGE RANGE. The dynamic heat transfer model of the multi-layer wall integrated with PCM layer is established and verified by the published data and the experimental data. Then the verification of the calculation method proposed in chapter 3 is carried out under the different PCM phase-change occurrence design period, the different locations of the PCM layer and the different wall structures. Covering rate of wall inner surface and outer surface temperature is proposed to evaluate the accuracy of PCM phase change range calculation method. Under three above verification cases, the PCM phase-change range obtained from the theoretical equation can guarantee the time of phase-change occurrence covers 90%~99% of the design periods.

In Chapter 5, CASE STUDY ON IMPROVEMENT OF WALLS THERMAL PERFORMANCE WITH PCM LAYER IN CHINA, quantitative analysis on improvement of multi-layer wall thermal performance with PCMs under air-conditioning continue running and intermittent running is done for the climate of Chengdu, China from three aspects: wall inner surface temperature, heat flow wave reduction rate and delayed time. Result shows that when the air conditioning is continues running, the improvement effect of wall thermal performance is best when the air condition running season covers PCMs phase change occurrences design case. Such as in summer, when the phase change range is designed according summer climate condition, the reduction rate of multi-wall surface temperature and heat flow is largest and the wave peak value delayed time is longest. In addition, even when designing PCM phase change range, some season is not included, wall inner surface also has a heat flow decrease rate because the PCM layer can add wall thickness. For different locations of PCM layer, the variation of wall inner surface temperature and heat flow is same and the closer of PCM layer to inner surface, the delayed time and wave peak decrease rate is bigger. For example, in summer, when L (distance between PCM layer and wall inner surface) is 0 mm, the decrease rate is 20.5% ; when L is 220mm, the decrease is 11.3%. When air conditioning is intermittent running, PCM layer in wall inner surface even decreases wall inner surface thermal response rate. When PCM layer is in wall outer surface, the thermal response rate can be increased in a certain extent. Especially for light-weight wall with PCM layer in inner surface, heat flow can increased by above 200%; however, for inner surface, it can be decreased by 10%~ 20%.

Chapter 6, CASE STUDY ON THERMAL PERFORMANCE IMPROVEMENT OF WOODEN WALLS INTEGRATED WITH PCMS LAYER IN JAPAN. Analysis on the thermal performance of a wooden wall with PCM layer under the Fukuoka whole year climate is done when the PCM layer is in different location of the wall. Among which, the typical period in summer and winter is selected for future analysis. In addition, the influence of heat conductivity coefficient and heat latent of the PCM on the wall energy saving is analyzed.

Chapter 7, CONCLUSIONS, the whole summary of each chapter has been presented.

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CHAPTER SEVEN: CONCLUSIONS

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Chapter One: Background and Purpose of The Study

1.1 Introduction

As the global energy consumption and people's demand on the indoor thermal comfort increases, the energy saving method has attracting more and more attention. Among the whole energy consumption, energy consumed in the buildings sector consists of residential and commercial end users and accounts for 20.1% of the total delivered energy consumed worldwide. In the International Energy Outlook 2016 (IEO2016) Reference case, delivered energy consumption in buildings worldwide increases by an average of 1.5%/year from 2012 to 2040. So improving building energy efficiency is a big importance for the worldwide energy saving business. Usually, there are two kinds' methods of improving buildings energy efficiency: passive technology and positive technology. Among the passive technology, using the thermal energy storage technology (TES) in envelops is more and more popular. TES can be accomplished either by using sensible heat storage or latent heat storage(using phase change materials). Sensible heat storage has been used for centuries by builders to store/release thermal energy, but a much larger volume of material is required to store the same amount of energy in comparison to latent heat storage. The principle of using phase change materials (PCMs) as a latent heat store materials is simple. When PCMs reach the temperature at which they change phase (their phase change range), they absorb large amounts of heat at an almost constant temperature. The PCM continues to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase. When the ambient temperature around PCMs falls, the PCMs solidifies and releases its stored latent heat.

1.2 Research background

1.2.1 Worldwide energy consumption situation[1]

During the past hundred years, energy consumption and environmental pollution has become more and more serious due to the continuous consumption of fossil fuels. And this trend in energy use is not sustainable not only because of the extensive emissions of local air pollutants, but also great press on the global environmental issues (CO2 emissions). Meanwhile, the worldwide energy consumption has been increasing rapidly since the industrial revolution. This increasing trend has also been accelerated by the improvement of people life quality that directly relates to the amount of energy consumption and the industrialization of the developing nations. Figure 1-1 shows world energy consumption significant growth from 1990 to 2040. Total world consumption of marketed energy expands from 549 quadrillion Btu in 2012 to 629 quadrillion Btu in2040, a 48% increase from 2012 to2040. Much of the increase in energy demand occurs among the developing non-OECD nations. The developing countries are going on strong economic growth and expanding populations. As shown in Figure 1-1, Non-OECD demand for energy rises from 310 quadrillion Btu in 2012 to 532 quadrillion Btu in 2040, a 71% increase from 2012 to 2040. Economic growth, along with accompanying structural changes, strongly influences world energy consumption. As countries develop and living standards improve, energy demand also grows rapidly. In countries experiencing rapid economic growth, the increasing population demands increasing houses number and improving the living conditions which need more energy. Over the past 30 years, world economic growth has been led by the non-OECD countries, accompanied by strong growth in energy demand in the region. From 1990 to 2012, real GDP grew by 4.9%/year in non-OECD countries, compared with 2.1%/year in OECD countries. In the future, the differences in economic growth rates between OECD and non-OECD nations are expected to narrow, as economic growth in non-OECD countries moderates, and as their industrial structures move from reliance mainly on production in energy-intensive industries to more service-oriented industries. Average GDP in the non-OECD region grows by 4.2%/year from 2012 to 2040, compared with 2.0%/year in the OECD as shown in Figure 1-2.

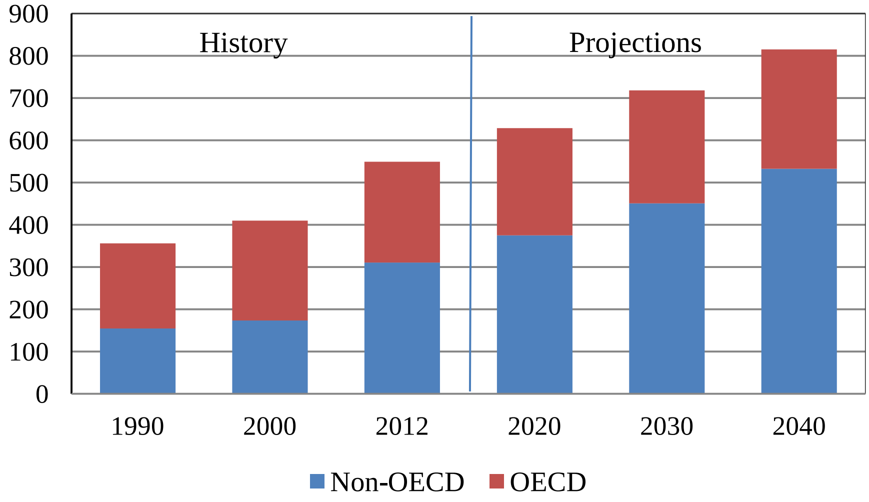

Figure 1-1 World energy consumption, 1990-2040 (quadrillion Btu)

Source: International Energy Outlook 2016

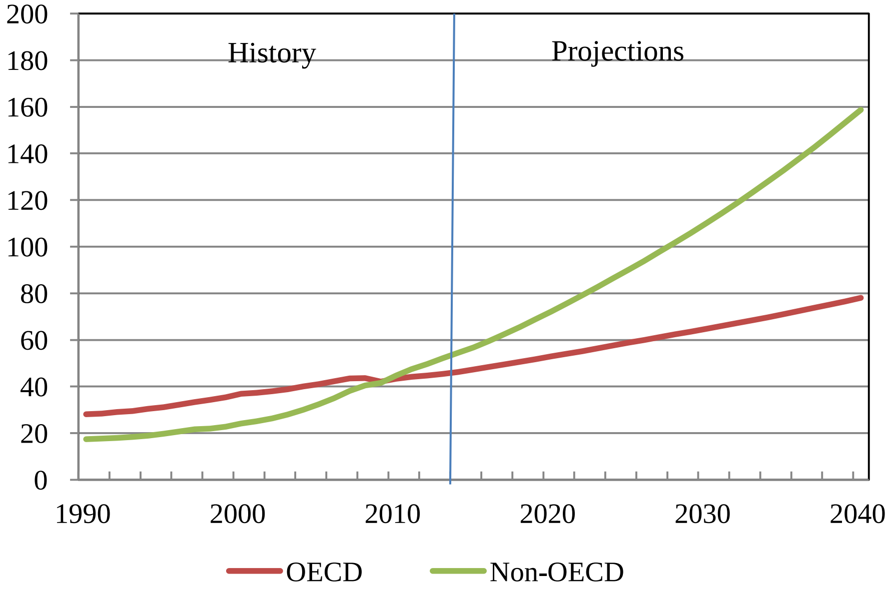

Figure 1-2 World total gross domestic product, 1990-2040 (trillion dollars)

Source: International Energy Outlook 2016

In addition, the energy consumption in Non-OECD by region from 1990 to 2040 has been shown in Figure 1-3**.** Then energy consumption of non-OECD Asia including China and India accounts more than half (About 83%) of the increase of that in non-OECD from 2012 to 2040. China and India, in particular, has been the world's fastest-growing economies over the past decades years. Although their economic expansion is expected to moderate in the future, they remain important areas of growths in world energy demand. Then is the Middle East, from 2012 to 2040, the energy consumption has a total increase of 95% (30 quadrillion Btu) because of the fast-paced growth in population and economy. Similarly, Africa's energy consumption in 2040 is two times of that in 2012, a total increase of 22 quadrillion Btu. The smallest increase is that of Europe and Eurasia, including Russia. The reason is the regions population declines and significant gains in energy efficiency are achieved by replacing old capital equipment with more efficient stock.

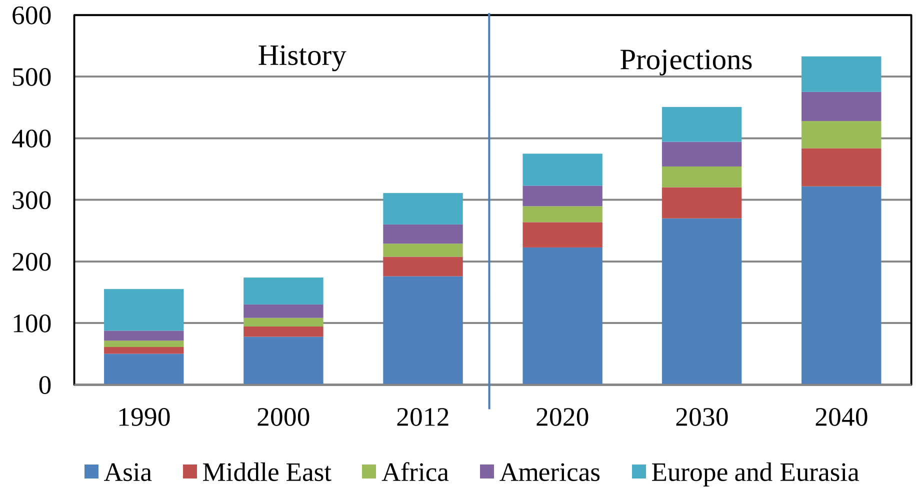

Figure 1-3 Non-OECD energy consumption by region, 1990-2040 (quadrillion Btu)

Source: International Energy Outlook 2016

From the aspect of energy source, as the attention about global energy saving problem and the government policies and incentives promoting the use of nonfossil energy sources in many countries, renewable energy has been the world's fastest-growing source of energy, at an average of rate of 2.6%/year, then is the nuclear energy use increases by 2.3%/year, and natural gas is 1.9%/year, as shown in Figure 1-4. However, fossil fuels are still the world's largest energy consumption even though the share of total world marketed energy consumption declines from 33% in 2012 to 30% in 2040. Liquid fuels, natural gas and coal account for 78% of the total world energy consumption. Coal is the slowest-growing energy source with 0.6% /year average increases from 2012 to 2040, slower than the 2.2%/year over the past 30 years.

World Energy-related CO2 emission by fuel is shown in Figure 1-5. CO2 emission from the use of liquid fuels, natural gas and coal all increase from 32.3 billion metric tons in 2012 to 35.6 billion metric tons in 2020 and to 4302 billion metric tons in 2040, with the relative contributions of the individual fuels shifting over time. In 1990, CO2 emission from the use of liquid fuels accounts for the largest portion (43%) of the global emissions. In 2012, they had fallen to 36% and remain the same level in 2040. Coal is the most carbon emission fuel became the leading fuel of world energy-related CO2 emission in 2006 and keeps the leading position until 2040. However, although coal accounted for 39% of the total emissions in 1990 and 43% in 2012, its share is projected to decline to 38% in 2040, only slightly higher than the liquid fuels share. The natural gas share of CO2 emissions, which was relatively small at 19% of total GHG emissions in 1990 and 20% in 2012, increases in the IEO2016 Reference case to 26% of total fossil fuel emissions in 2040.

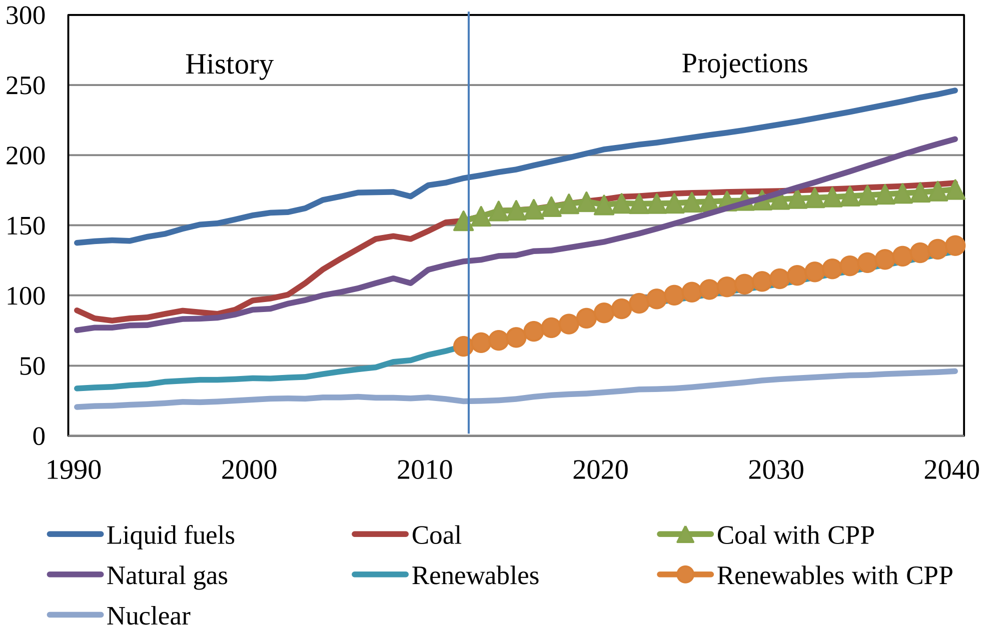

Figure 1-4 World energy consumption by energy source, 1990-2040 (quadrillion Btu)

Source: International Energy Outlook 2016

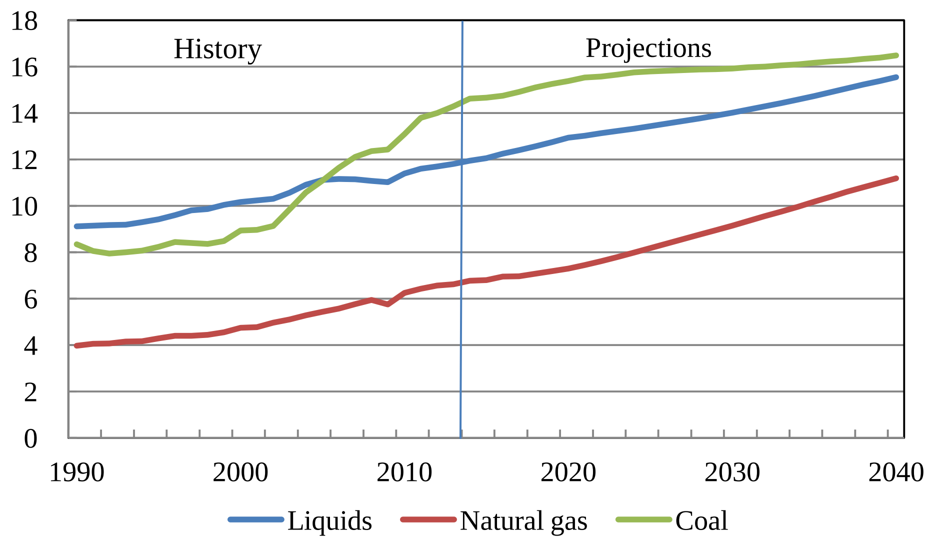

Figure 1-5 World energy-related carbon dioxide emissions by fuel type, 1990-2040 (billion metric tons)

Source: International Energy Outlook 2016

1.2.2 Worldwide building energy consumption situation

Nowadays, most people spend 90% of their daily lives indoors and their comfort is relying on mechanical heating and air conditioning, thus leading to buildings becoming the largest energy consumers worldwide. Energy consumed in buildings sector consists of residential and commercial end users have accounted for 20.1% of the total energy consumed worldwide. Delivered energy consumption in buildings worldwide increases by an average of 1.5%/year from 2012 to 2040. In the non-OECD nations, energy consumption in buildings grows by 2.1%/year from 2012 to 2040. The ratio of building energy consumption to total energy consumption increased from 33.7% to 41.1% between 1980 and 2010 in the US. The EIA predicted that the growth would slow down due to the economic recession. Building energy consumption in china increased 40% from 1990 to 2009. Then China has become the second largest building energy consumer in the world. Chinese building energy consumption has a percentage of 27.3% of the total energy consumption in 2010.

Energy consumption in the residential buildings includes energy used for heating, cooling, lighting, water heating and consumer products. And it is affected by income levels, energy prices, location, building and household characteristics, weather, efficiency and type of equipment, energy access, availability of energy sources and energy-related policies, among other factors. As a result, residential buildings energy consumption varies significantly with regions and countries. According the IEO 2016, energy consumption in residential sector accounts for about 13% of the total world energy consumption in 2040, growing by an average of 1.4%/ year from 2012 to 2040. And the increase of OECD is much slower with a 0.6%/ year as shown in Figure 1-6. The sequence of residential energy consumption in OCED countries from large to small is Mexico/Chile (1.9%), Australia/New Zealand (1.7%), South Korea (1.1%), OECD Europe (0.9%), Canada (0.7%), Japan (0.4%), U.S (0.1%.).The reason may be the relatively slow growth in GDP and population, as well as improvements in building shells and the efficiency of appliances and equipment. However, residential sector energy consumption per capita in OECD is shown in Figure 1-7. OECD residential energy use per capita grows by an average of 0.2%/year.

Residential energy consumption in the non-OECD countries accounted for less than 50% of the world’s total residential energy use in 2012. There share grows to nearly 60% in 2040. Figure 1-8 and 1-9 shows annual change of the residential energy consumption and energy consumption per capita in non-OECD region. Total residential sector demand for energy in the non-OECD countries increases by an average of 2.1%/ year. China and India account for 27% of the world’s residential energy consumption, up from 19% in 2012. India is always the leading role with an average annual increase of 3.2% from 2012 to 2040. Residential energy use in China grows by an average of 2.4%/year from 2012 to 2040. And has becomes the largest residential energy consumer. The rapid growth in China's residential sector energy consumption is mainly because of strong economic growth and urbanization, as lifestyle and energy use patterns vary widely between urban and rural populations[3]. According to the United Nations, nearly three-fourths of the Chinese population will live in urban areas by 2040 [4]. China's demand for energy services increases as per capita income and quality of life improve accompanied by an increase in urban population and increased access to nontraditional fuels in rural areas. China's residential energy use per capita grows by 2.3%/year from 2012 to 2040 (Figure 1-9).

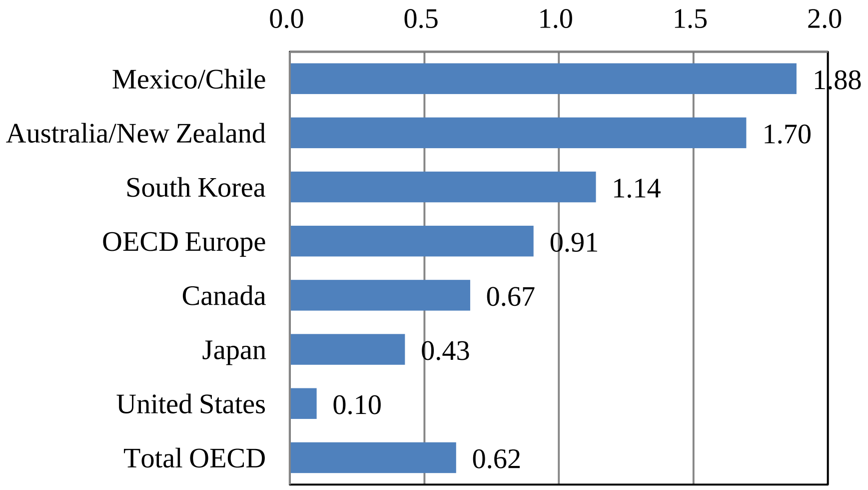

Figure 1-6 Average annual change in OECD residential sector energy consumption, 2012-2040 (percent per year)

Source: International Energy Outlook 2016

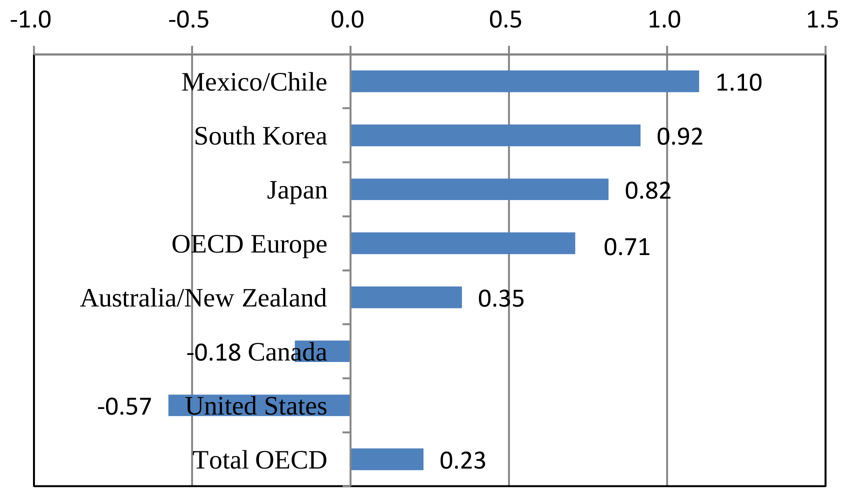

Figure 1-7 Average annual change in OECD residential sector energy consumption per capita, 2012-2040 (percent per year)

Source: International Energy Outlook 2016

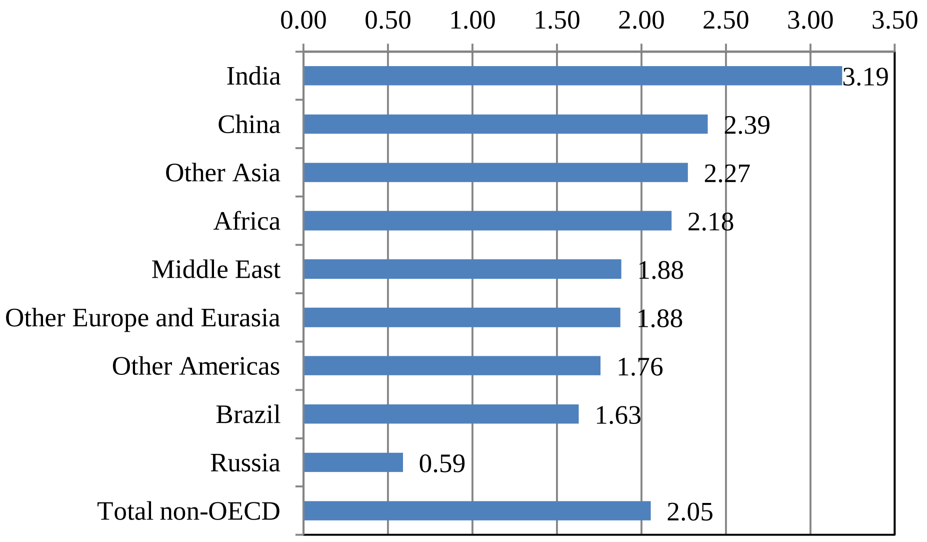

Figure 1-8. Average annual change in non-OECD residential sector energy consumption, 2012-2040 (percent per year)

Source: International Energy Outlook 2016

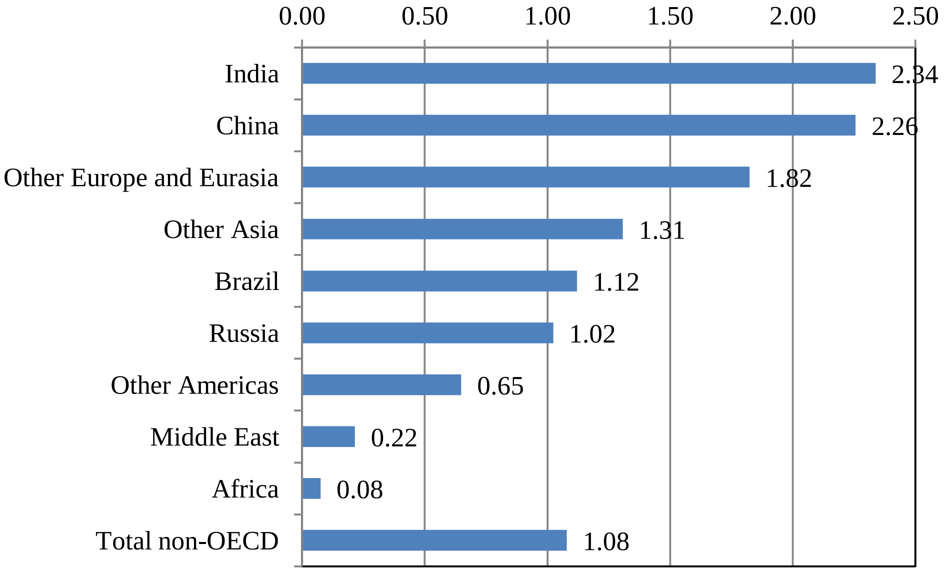

Figure 1-9 Average annual change in non-OECD residential sector energy consumption per capita, 2012-40 (percent per year)

Source: International Energy Outlook 2016

1.2.3 Thermal energy storage (TES)

Thermal energy storage (TES) is very helpful for meeting society's needs and desires for more efficient, environmental energy in applications such as building passive energy saving technologies, power generation and distribution. The use of TES systems has many advantages such as the following:

1) Reduced energy costs
2) Reduced energy consumption
3) Improved indoor air quality
4) Increased flexibility of operation
5) Decreased initial and maintenance costs
6) Reduced equipment size
7) More efficient and effective utilization of equipment
8) Conservation of fossil fuels
9) Reduced pollutant emissions

Thermal energy storage (TES) is essential for reducing dependency on fossil fuels and then contributing to improving energy utilization of buildings. Various types of TES technologies exist, such as sensible heat TES. It stores heat in fluid or solid form. Another is latent heat TES, which releases and stores latent heat during the phase change process. TES can rapidly release or store large amounts of heat because solar energy and heat are intermittent heat sources [5]. It is an attractive technology because it is the most appropriate method of correcting the gap between the demand and supply of energy [6]. An overview of major technique of thermal energy storage is shown in Figure1-10 [7-8]. Figure 1-11 shows a comparison of the heat storage process of these primary ways[9-10].

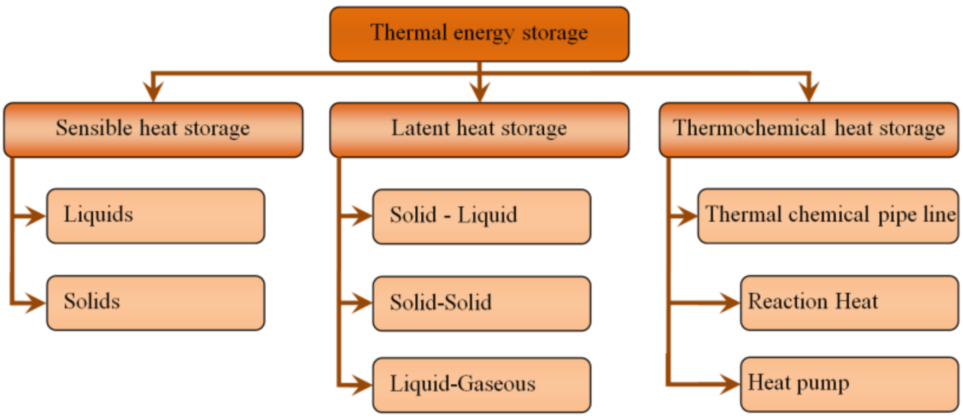

Figure 1-10 An overview of major technique of thermal energy storage

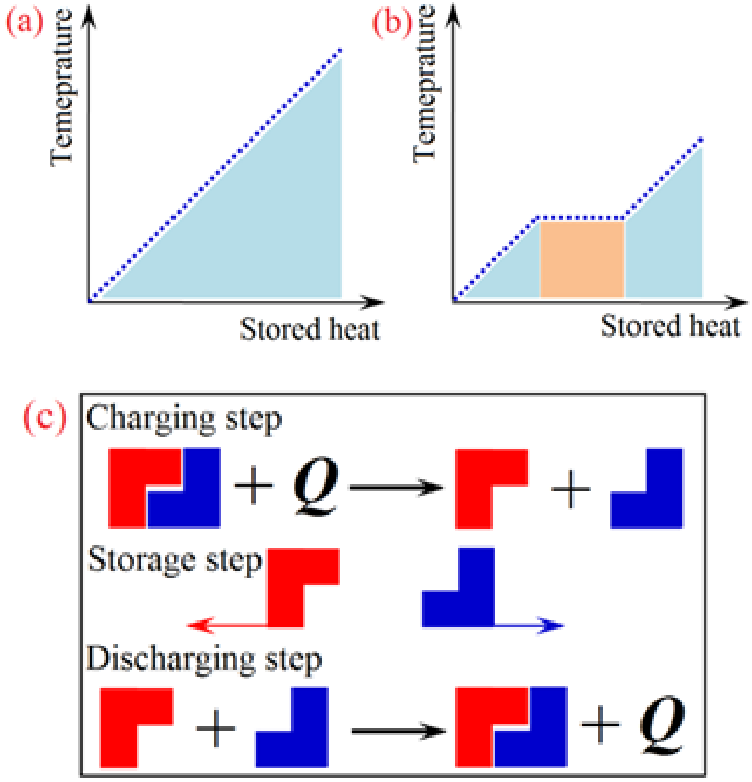

Figure 1-11 A comparison in (a) sensible heat storage, (b) latent heat storage and (c) thermochemical heat storage

(1) For the sensible heat storage, thermal energy can be stored in a temperature increase in the material of a solid or liquid. The sensible heat storage system utilizes the heat capacity and the temperature change of the material during the process of charging and discharging. The amount of heat stored depends on the specific heat of the medium, the temperature change and the amount of storage material, as following:

$$Q = \int_{T_i}^{T_f} mC_P dT = mC_P \left(T_f - T_i\right) \tag{1-1}$$

As the common sensible heat storage material, water appears to be the best sensible heat storage liquid available because it is inexpensive and has a high specific heat of 4190J/(kg·K).

(2) For the latent heat storage, thermal energy can be stored or released, when a material undergoes a phase change from solid to liquid or liquid to gas or vice versa. The amount of stored energy can be determined by:

$$Q = \int_{T_i}^{T_m} mC_{SP} dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mC_{LP} dT \tag{1-2}$$

$$Q = m\left[C_{SP}\left(T_m - T_i\right) + ma_m \Delta h_m + C_{LP}\left(T_f - T_m\right)\right] \tag{1-3}$$

The materials used for latent heat energy storage (also called the phase change materials) have the characteristic of absorbing or releasing thermal energy via temperature variations in controlled conditions. Singular storage capacity with small temperature intervals and generally negligible volume changes are the key advantages of PCMs, which allow them to be successfully implemented in buildings for thermal management.

(3) For the thermochemical heat storage, thermal energy can be stored or released, when molecular bonds are broken and reformed in a completely reversible chemical reaction. In this case, the heat stored depends on the amount of storage material, the endothermic heat of reaction, and the extent of conversion, as following:

$$Q = a_{\mathrm{r}} m \Delta h_{\mathrm{r}} \tag{1-4}$$

Among above thermal heat storage techniques, latent thermal energy storage is particularly attractive due to its ability to provide high-energy storage density and its characteristics of storing heat at a constant temperature corresponding to the phase change temperature of phase change material.

1.3 Previous study

Many studies have been reported on the application of PCMs in building envelops. Ordinary building materials such as concrete and gypsum only represent the sensible heat storage capacity. Its heat storage capacity varies between 0.76 and 1 kJ/(kg.K). Whereas, phase change materials such as paraffin may have latent heat storage capacity of approximately 110kJ/kg. Due to high heat storage potential, storing the same amount of thermal energy needs a much smaller volume of the materials. Another advantage of PCMs is that envelops temperature within PCM remains almost constant. However, even though there are so many advantages mentioned and a lot of the research projects on PCMs, most of the PCM products do not find commercial implementation in building envelops. Even some of them are implicated in buildings, there are few real case studies on the performance in buildings, and most information is limited to the laboratory test. This section just describes the previous study of PCMs in buildings envelops.

Many people have make research on application of PCM in building walls in experimental method and numerical simulation method. XU WANG[11-12] make small-scale and full scale experiment on a kind of composite wall incorporated with shape-stabilized phase change materials(SSPCMs) in a full room in Shanghai. Results show a reduction of about 0.2 ℃ for the maximum interior wall surface temperature, a time delay of about 1-2 h of temperature amplitude and a reduction of 24.32% of the cooling load for the PCM-wall in summer. For the midseason cases, the PCM-wall was under the phase transition temperature range and could completely resist the ambient thermal disturbance. For the winter cases, the PCM-wall could reduce 10-30% of the heating load. Figure 1-12 is the experiment photo. Figure 1-13 is the full scale experiment photo.

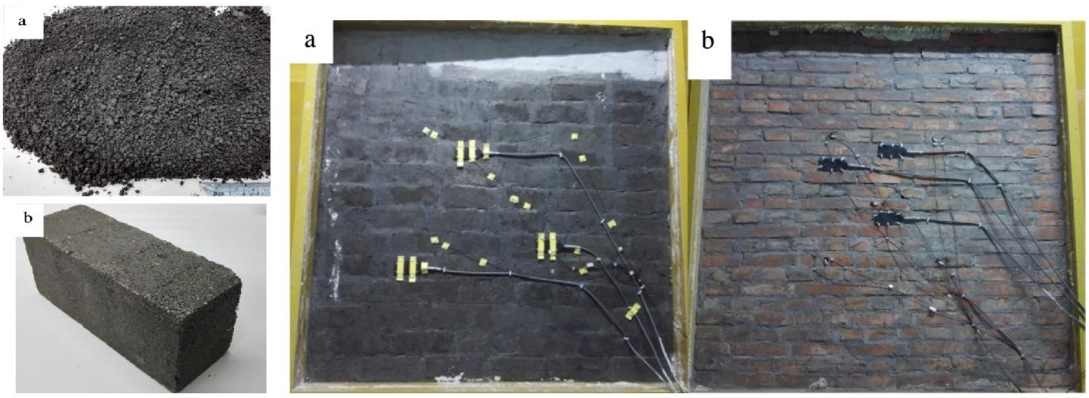

Figure 1-12 Appearance of (a) PCMs-wall and (b) common wall[11]

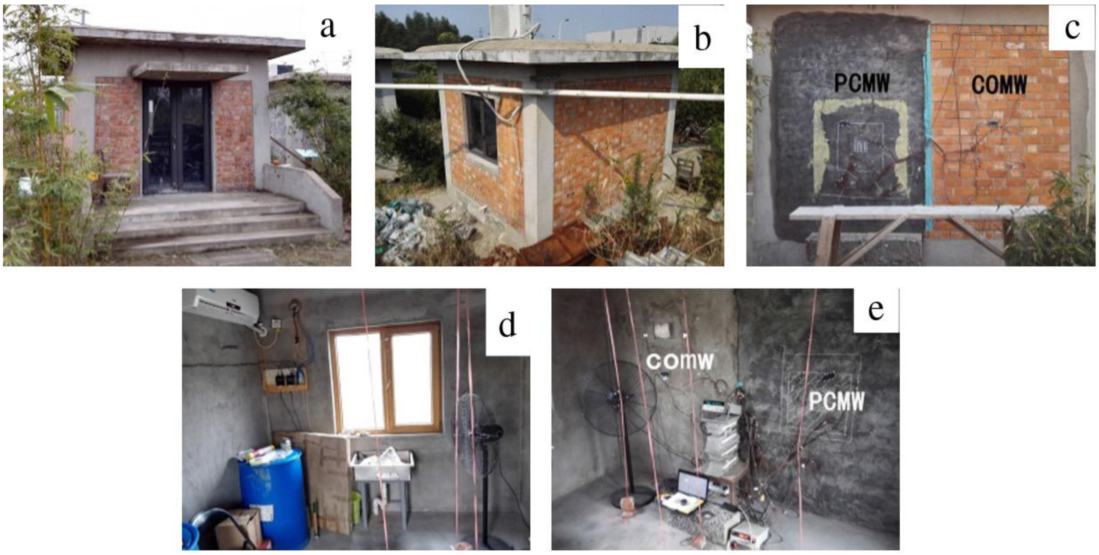

Figure 1-13 Full-scale experiment photo[12]

Ahmad M al[13] make a small experiment on light wallboards coupling vacuum isolation panels and phase change material using a test-cell. The research object is shown in Figure 1-14. Results shows the efficiency of PCM is remarkable with a reduction of the indoor temperature amplitude of approximately 20^{o}C in the test cell. In summer the amplitude of the temperature inside the cell with PCM is decreased by 20 ^{o}C on a daily cycle. In winter, this prevents negative indoor temperature whilst the temperature of the cell without PCM is -9 ^{o}C and that the outside temperature is below -6 ^{o}C.

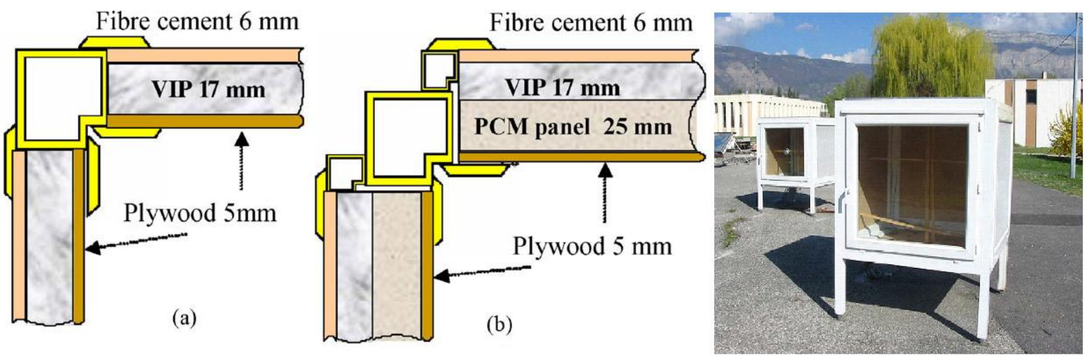

Figure 1-14 Test cell of light wallboards coupling vacuum isolation panels and phase change material[13]

Panayiotou G.P et al. made evaluation of the application of PCM on the envelope of a typical dwelling in the Mediterranean region using TRANSYS. Result shows the energy savings achieved by the addition of the PCM layer on the envelope of the test cubicle compared to the base case (no insulation) ranged between 21.7% and 28.6%. The optimum PCM case was also combined with a common thermal insulation topology in Cyprus. The results showed that the maximum energy savings per year was achieved by the combined case (66.2%). In the temperature level control test, the constructions containing PCM performed better during summer. The results of the optimum PCM case and the combined case were economically evaluated using Life Cycle Cost (LCC). The results of this analysis showed that the PCM case has a very long payback period (14.5 years) while this is changing when it is combined with insulation where the payback period is reduced to 7.5 years.

Cabeza LF et al [14]makes full scale experiment research using PCM in brick constructive solutions for passive cooling in Puigverd de Lleida, Mediterranean. Result shows the PCM can reduce the peak temperature up to 1 ^{o}C and smooth out the daily fluctuations. In summer of 2008 the electrical energy consumption was reduced in the PCM cubicles about 15%. These energy savings resulted in a reduction of the CO2 emissions about 1-1.5kg/year/m2.

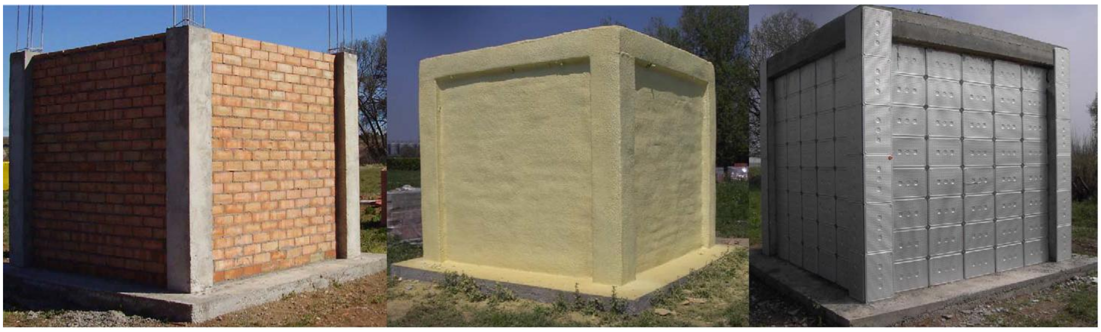

Figure 1-15 Comparison cubicles: brick cubicle, brick cubicle with polyurethane, brick cubic with RT-27 and polyurethane[14]

Evers A.C [15] make small-scale experiment on thermal performance of frame walls enhanced with papraffin and hydrated salt phase change materials using a dynamic wall simulator. And result shows that the PCM-enhanced insulation reduced the average peak heat flux by up to 9.2% and reduced the average total daily heat flow up to 1.2%.

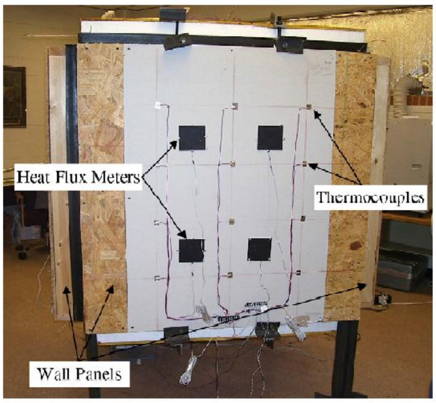

Figure 1-16 Research object [15]

Mi X.M.et [16] made energy and economic analysis of buildings integrated with PCM in different cities of china. Result shows that the energy savings resulting from PCM application are more prominent for office building located in cold region. For economic analysis, the application of PCM in Shenyang, Zhenzhou and Changsha showed high economic value and the investment appeared to be attractive. However, at current prices, the PCM investment in Kunming and HongKong cannot be recovered and do not offer economic benefits. Figure 1-17 is the Schematic of PCM wall in this literature.

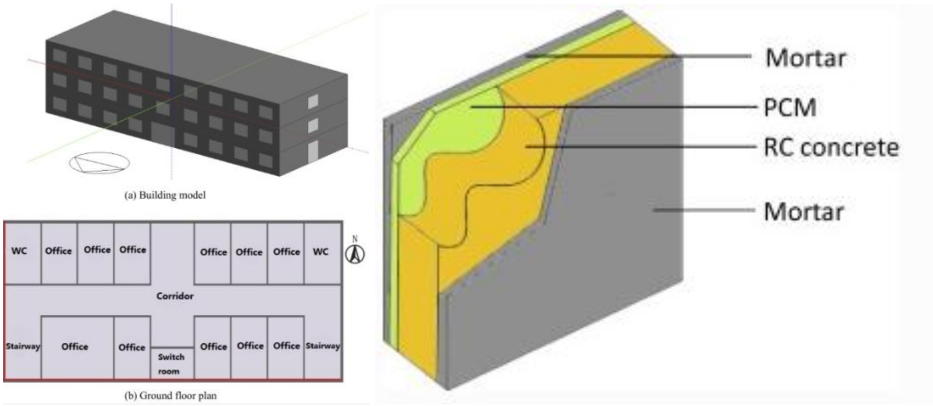

Figure 1-17 Schematic of PCM wall. [16]

Kheradmand M et al [17] made experimental and numerical studies of hybrid PCM embedded in plastering mortar for enhanced thermal behaviour of buildings. Results shows that this structure have the potential to significantly reduce heating/cooling temperature demands for maintaining the interior temperature within comfort levels when compared to normal mortars (without PCM), or even mortars comprising a single type of PCM.

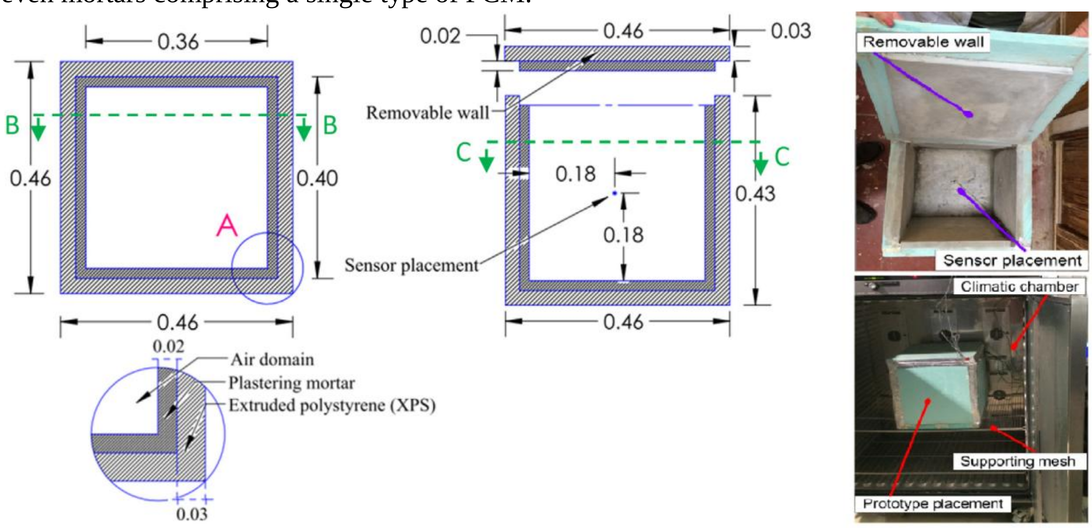

Figure 1-18 Schematic representation and sensor placement of the prototypes[17]

Barrenech C et al[18] made full scale experiment in Puigverd de Lleida, Spain on in situ thermal and acoustic performance and environmental impact of the introduction of a shape-stabilized PCM layer for building applications. Result shows that the PCMs dense sheet presents better thermal behavior, better acoustic insulation properties and the leaching test show similar results. Therefore, it can be applied in real building as part of walls where acoustic and thermal aspects need to be improved.

Shi X et al [19] make experimental assessment of position of macro encapsulated phase change material in concrete walls on indoor temperatures and humidty levels. The results shows while the optimal location was closer to the interior surface of the wall when the interior surface temperature of the wall was increased.

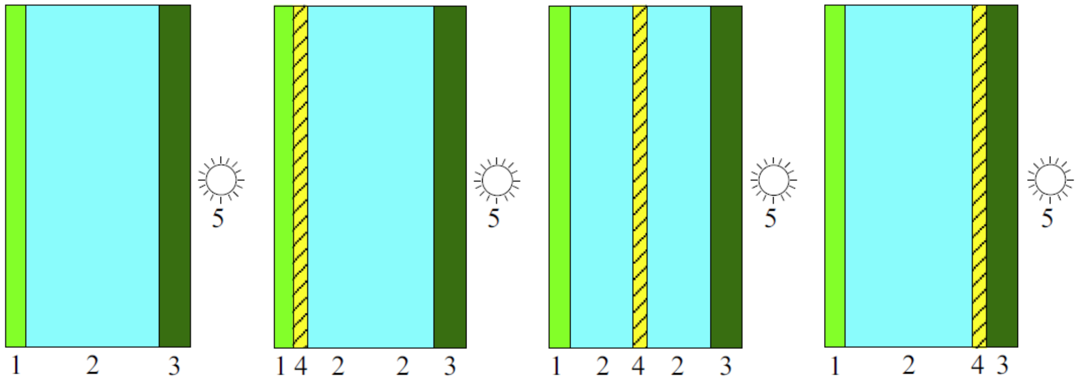

Figure 1-19 Position of the PCM layer in walls[19]

Zhu N et al[20] make numerical simulation on the performance of a novel double shape-stabilized phase change materials wallboard in Wuhan, china. Figure 1-20 is the room model. Result shows that for internal and external SSPCM wallboard, the optimum thickness was between 30mm and 60mm in an air-conditioned office, and a high reduction of the inner surface temperature of the wallboard was prevented by the internal SSPCM wallboard; the annual and peak loads of cooling energy savings were reduced by 3.4~3.9% and 3.1%~3.8%, while the annual and peak loads of heating energy savings were reduced by 14.8%~18.8%.

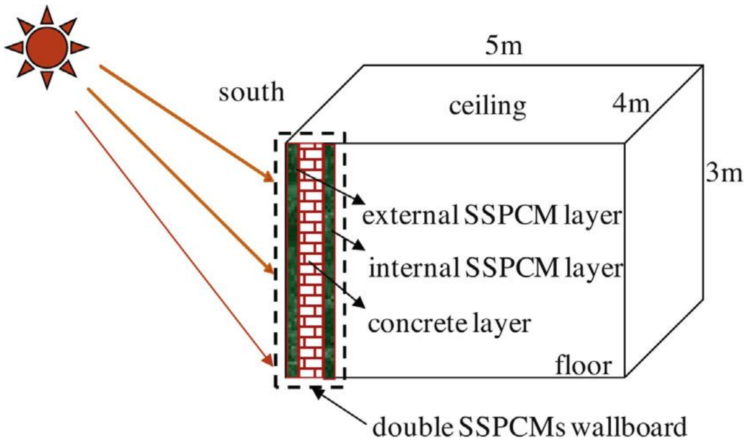

Figure 1-20 mode of double SSPCMs wallboard [20]

Lee KO [21]make full scale experiment on a thin phase change material (PCM) layer in a residential building wall in Lawrence, KS, USA. The optimum location for the PCM layer in south wall and the west wall would be location 3 and 2, based on heat flux reduction were 51.3% and 29.7% for the south wall and west wall. The maximum peak heat flux time delays were 6.3 h for location 1 in the south wall and 2.3 h for location 2 in the west wall. The maximum daily heat transfer reductions were 27.1% for location 3 in the south wall and 3.6% for location 5 in the west wall.

Figure 1-21 Location of PCM and appearance of the experimental house[21]

Table 1-1 List of researches on application of PCM in the external walls

Authors	Properties and type	Method	Content
Wang X. et al.[11]	20-24 ℃ for phase change temperature arrange;33.25 J/g	Experiment	Experimental assessment on a kind of composite wall incorporated with shape-stabilized phase change materials (SSPCMs)
Wang X. et al[12]	A mixture of expanded graphiteparaffin wax and high-density polyethylene	Full-scale experiment	Experimental assessment on the use of phase change materials (PCMs)-bricks in the exterior wall of a full-scale room
Ahmad M et al [13]	21-25 ℃ for melting 148J/g Polyethylene glycol	Small-scale experiment	Thermal testing and numerical simulation of a prototype cell using light wallboards coupling vacuum isolation panels and phase change material
Panayiotou G.P. et al. [14]	29 ℃ for melting 25.09 ℃ for freezing 165 -200J/g for latent heat Paraffin	Numerical simulation	Evaluation of the application of Phase Change Materials (PCM) on the envelope of a typical dwelling in the Mediterranean region
Cabeza LF et al. [15]	28 ℃ and 26 ℃ for melting 26 ℃ and 25 ℃ for freezing Paraffin and hydrate salt	Full-scale experiment	Experimental study of using PCM in brick constructive solutions for passive cooling
Evers A.C. et al. [16]	29 ℃ for melting 26 ℃ for freezing 175J/g Paraffin, hydrated salt and cellulose insulation	Small-scale experiment	Evaluation of the thermal performance of frame walls enhanced with paraffin and hydrated salt phase change materials using a dynamic wall simulator
Mi X.M. et al. [17]	27 ℃ for melting	Numerical simulation	Energy and economic analysis of building integrated with PCM in different cities of China

Kheradmand M et al [18]	2-12 ℃, 12-25 ℃, 10-30 ℃,22-32 ℃ for phase change temperature arrange;	Small-scale experiment numerical simulation	Experimental and numerical studies of hybrid PCM embedded in plastering mortar for enhanced thermal behaviour of buildings
Barreneche C et al [19]	21 ℃ for melting 160 J/ g 17% polymeric matrix, 12% paraffin and 71% Electrical arc furnace dust	Full-scale experiment	In situ thermal and acoustic performance and environmental impact of the introduction of a shape-stabilized PCM layer for building applications
Shi X et al. [20]	179kJ/kg RT27	Numerical simulation	Experimental assessment of position of macro encapsulated phase change material in concrete walls on indoor temperatures and humidity levels
Zhu N et al. [21]	15-45 ℃ for melting 12-25 ℃ for freezing 200kJ/kg and 190kJ/kg for latent heat Paraffin	Numerical simulation	Modeling and simulation on the performance of a novel double shape-stabilized phase change materials wallboard
Lee KO et al. [22]	31.4 ℃ for melting 149.9 kJ/kg for latent heat hydrated salt	Full scale experiment	Assessing the integration of a thin phase change material (PCM) layer in a residential building wall for heat transfer reduction and management
Biswas K. and Abhari R. [23]	16.5 ℃-26.5 ℃ 116.7 kJ/kg for latent heat	Full scale experiment numerical simulation	Low-cost phase change material as an energy storage medium in building envelopes: Experimental and numerical analyses
Kong XF, et al [24]	27.9 ℃ and 26.1 ℃ for melting 30.2 ℃ and 26.5 ℃ for freezing 142.7 kJ/kg and 126.9kJ/kg for latent heat Capric acid	Full scale experiment Numerical simulation	Experimental research on the use of phase change materials in perforated brick rooms for cooling storage

Kong XF et al [25]			Numerical study on the thermal performance of building wall and roof incorporating phase change material panel for passive cooling application
Lu S.L. et al [26]	28 ℃ for melting 25.01 ℃ for freezing 103.5-119.8 for latent heat A mixture of capric acid and dodecanol	Experiment and numerical simulation	Establishment and experimental verification of PCM room's TRNSYS heat transfer model based on latent heat utilization ratio

1.4 Research objective and outline

The review of existing studies can suggest the tendency of application of PCM in buildings and shows that the PCM layer has a obvious effect on decreasing the building energy consumption, refining the indoor thermal comfort, shifting and reducing the peak electricity load in particularly. However, the above researches focus on the properties of PCM and improvement effect of PCM on buildings thermal environments. All of them are based on given PCM properties. For a certain climate condition and wall structure, how to make sure PCM phase change range and select PCM materials, it is unknown. That means there lacks of demand-user methods of selecting PCM for different envelopes and the coupling studies of PCM thermal physical properties with envelope structures, indoor and outdoor thermal environment. So this paper proposed a theory calculation method of phase change range of PCM when it is used in multi-walls according the heat transfer law. In order to verified the accuracy of the theory calculation method, heat transfer model of enthalpy-porosity model is built and verified by published data and experiment data. Then the enthalpy porosity model is used for selecting a appropriate phase change range of PCMs and verifying the accuracy of phase-change rang obtained according theory calculation method under the different design periods of phase-change occurrence, the different location of the PCM layer and different structure of the multi-layer wall. It will also employ the model to make research on improvement on wall thermal performance with PCMs under air-conditioning continue running and intermittent running mode in China and Japan. For the climate of Fukuoka, Japan, the improvement on thermal performance of a wooden wall with PCM is studied. Figure 1-22 is the research framework.

❖ Background study

CHAPTER ONE investigates the global energy consumption situation, global building energy consumption situation and TES technology. The previous studies about the PCM application in buildings envelops is reviewed.

CHAPTER TWO the basic properties of PCMs such as characteristics, selection criteria for the PCM suitable to building envelopes, incorporation methods of PCM into building wall are introduced. The development of PCM application in building walls are investigated. Then the research status of PCMs in buildings in Japan and China have been investigated.

❖ Theoretical study

CHAPTER THREE according the rule of PCM phase change in building walls, principle of PCM phase change range is proposed. Then based on the theory analysis of heat transfer laws, the calculation equations of the phase-change range are got and some limitations are given. Then according calculation equation, factors including outdoor temperature and wall structure influencing the range have been analyzed.

- ❖ Verification of the calculation method

CHAPTER FOUR, the heat transfer model of the multi-layer walls integrated with the PCM layer is established and verified by the experimental data and the published data. Then appropriate phase change range of PCM and the verification of the calculation method proposed in chapter 3 using the model is carried on under the different PCM phase-change occurrence design period, the different locations of the PCM layer and the different wall structures.

- ❖ Case study

CHAPTER FIVE, under the climate condition of Chengdu, China, we firstly make research on the improvement effect of PCM layer on multi-wall thermal response and energy conservation under different phase change range designing case, different location of PCM layer and different wall structures for the air conditioning continue running model. Then improvement effect on thermal performance of walls integrated with PCMs under air conditioning intermittent running in summer is also done in Chengdu, China.

CHAPTER SIX, analysis on the thermal performance of a wooden wall with PCM layer under the Fukuoka whole year climate when the PCM layer in different location of the wall. Among which, the typical period in summer and winter is selected for future analysis. In addition, the influence of heat conductivity coefficient and heat latent of the PCM on the wall energy saving is analyzed.

- ❖ Conclusion

CHAPTER SEVEN, the whole summary of each chapter has been presented.

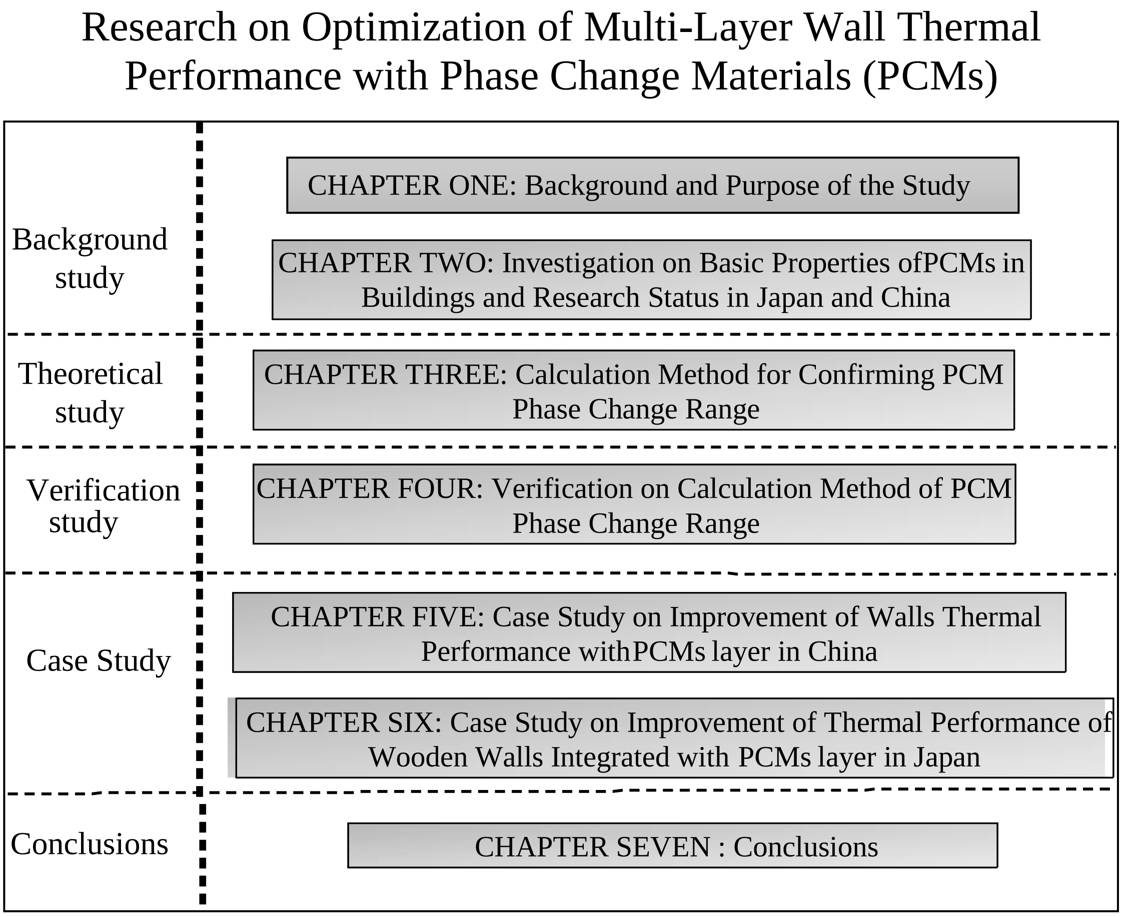

Figure 1-22 Research outline

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Chapter Two: Investigation on Basic Properties of PCM in buildings and Research Status in Japan and China

2.1 Introduction[1-2]

The global market for advanced Phase Change Materials (PCM) is projected to reach US$ 1.5 billion by 2020. It is because the strong emphasis on energy conservation, severe standards for greenhouse gases emission, demand for indoor thermal comfort, rising preference for biodegradable materials, recovering construction industry and rapid urbanization in developing countries. Europe represents the largest market worldwide because of the stress of strict building energy efficiency regulations across the region and higher awareness of the advantages of using energy efficient technologies. Asia-pacific is forecast to be the fastest growing market of PCM. Key factors of this phenomenon is the growing population, rapid urbanizations and amount of demand for healthy residential, commercial and infrastructure construction activity.

Building energy consumption has up to 40% of total consumed energy (Figure2-1). The energy consumed is higher than needed to provide comfort and functions which can cause more greenhouse emission and energy crisis. Now, majority of buildings was built using conventional building materials: brick and mortar, concrete, steel or timber frames for structural components, insulation for reduction of the air conditioning load and plaster walls within the buildings. Even insulation layer is helpful for stopping the temperature vary greatly by making the different parts of walls have similar thermal conductivity. A concrete wall may have a significantly higher thermal mass than a wooden wall in the frame per unit of volume. Residential buildings sector is the largest potential for energy saving as described in Chapter 1. The consumption in a building is affected by many factors such as characteristics of the structure, energy joints in the buildings, climate conditions and users' habits. Figure 2-2 shows the heat losses of a building.

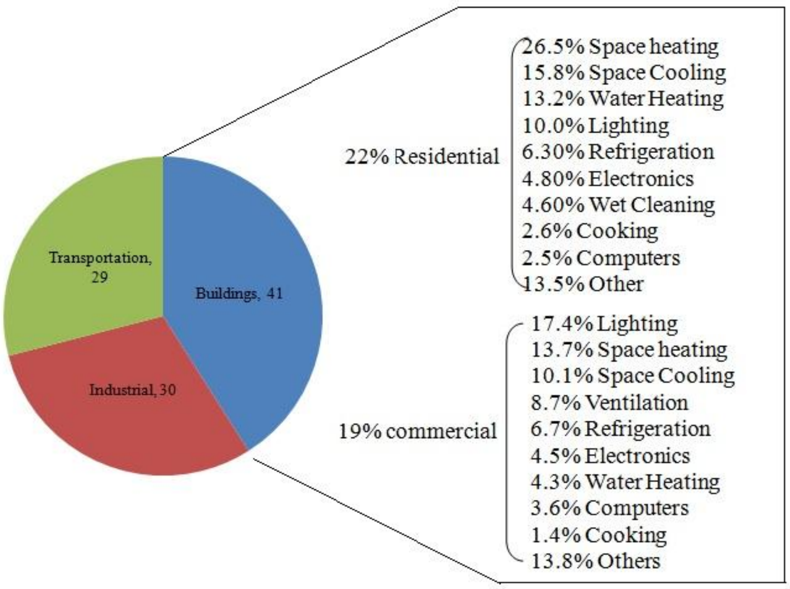


Figure 2-1 Energy consumption by sectors expressed in percents

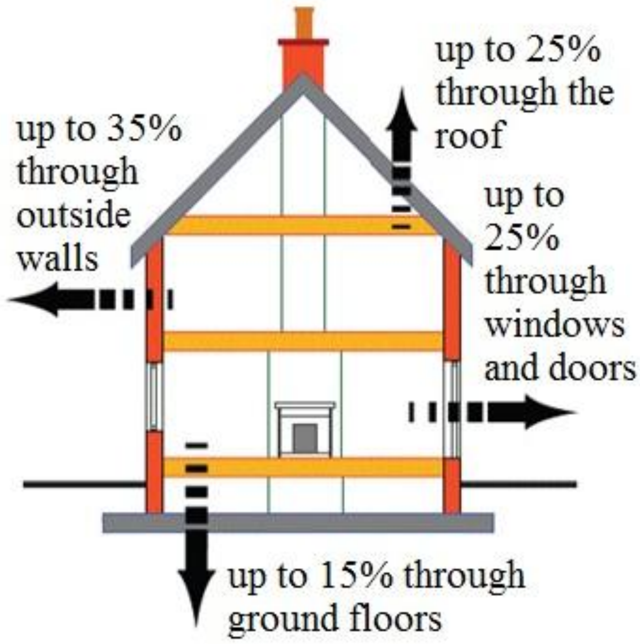


Figure 2-2 Heat losses of a building

PCM is used to store the latent energy and it is an efficient way of storing thermal energy. In buildings, there are many aspects that can use PCM for energy saving and indoor comfort. Such as heating, ventilation, air conditioning, and refrigeration (HVAC), and building & construction. They have constitute the largest end-use markets for PCM. Recently, PCM are always embedded inside the building envelope in the form of panels or boards and have the function of significant energy saving by trapping heat within the substrate. This method can lower building indoor temperature rise rate and causing a delay in peak load conditions. In HVAC applications, through regulation of the temperature fluctuation, the energy saving can achieved over 30%. As the heat loss through wall is up to 35%, so improving the energy saving from building walls is very important for building energy conservation. If building walls can use materials such as active thermal components (such as PCM), there will be an ultimate step in achieving significant heating and cooling energy savings. The key benefit of using PCM is that it affords structures improved thermal storage capabilities with minimal change to the existing building design. The main methods of integrating PCM into buildings contains the use of gypsum plaster boards and other structural boards, blending PCM with thermal insulations.

So this chapter mainly investigated the characteristics of PCMs and the development of PCM application in building walls and the research status in Japan and China

2.2 Phase Change Materials (PCM)

The global demand for air conditioning has increased significantly in the past decade and huge demands in electric power consumption have led to increased interest in energy efficiency and conservation. Energy consumption in buildings varies significantly during the day and night according to the demand by business and residential activities. In hot climate areas, most of the energy is consumed during the day time due to high ambient temperatures and intense solar radiation. This has led to varying pricing system for the on-peak and off-peak periods of energy use. Potential cost savings by reduction in energy consumption and by shift of peak load during the day can be achieved by incorporating PCMs in the envelope of residential and business building envelops.

Phase Change Material (PCM) is a useful remedy when there is a mismatch between the supply and demand of energy. There are many methods of using PCM storage systems for buildings, as demonstrated by the following concepts: a) equipments such as domestic hot water tanks which desiring the phase change melting temperature around 60 °C [3,4]. Another is heat transfer system[5,6], different PCMs used in different heat exchange configuration to enhance the heat transfer in system. PCM with cascaded latent heat storages is also used in solar energy utilization [7-9] for stem generation and concentric solar power plant. b) Used in building component for space cooling and heating in buildings and building energy conversation[10-12]. PCM is always used in walls, ceiling and gypsum boards, trombe wall and floor heating to break up the rising from solid to liquid.) Cold storage systems (chilled water storage system, ice storage system and eutectic salt storage system) that used as an effective mean of shifting peak electrical load. d) Industrial applications. Thermal protection of food: transport, hotel trade and ice cream.

One of the other potential applications of PCMs in buildings is to conserve energy. The use of PCM in buildings can deliver possible energy savings and peak load time shift. By offsetting the occurrence of peak load, few power plants can be operated to meet the load requirements. This saves initial cost, operating cost of the power plants and reduces harmful emissions. So far many researches about the use of PCM in building envelop have been done, and the concrete information will be introduced at the section of previous research.

2.2.1 PCMs and their classification

Changing of material phase can be classified into four states: solid–solid, solid–liquid, gas–solid and gas–liquid. For practical purposes, only the solid–liquid variety can be used for building cooling or heating due to the technical limitations of other varieties (for example small latent heat of solid–solid, the large volume changes of gas–solid and gas–liquid). In 1983, Abhat introduced a valuable classification of PCMs for thermal energy storage applications. Based on the chemical composition, PCM for solid–liquid phase change can be classified as organic (including paraffins and non paraffins), inorganic (including salt hydrates and metallic) and eutectic (including inorganic-inorganic organic-organic, organic-inorganic). Each group of PCM with their properties, advantages and limitations have been comprehensively reported in various literatures. An attempt is made here to compile the same in a tabular form as shown in Table 2-1.

Table 2-1 Comparison of different group of PCM [13-20]

Comparison aspect	Organic PCM		Inorganic PCM		Eutectics (Inorganic-inorganic)
	Paraffins	Non Paraffins (fatty acids, ester, glycols, etc)	Salt hydrates	Metallic	
Formula	C_nH_{2n+2} (n=12~38)	---	AB nH_2O	---	---
Melting temperature	-12~75.9 ℃	-7-187 ℃	8~117 ℃	-38.87~271.4 ℃	-10~142 ℃
Latent heat capacity	170~269 kJ/kg	120~258 kJ/kg	68~289 kJ/kg	11.4~433.8 kJ/kg	95~271.9 kJ/kg
Features	●Melting point and latent heat increases with chain length. ●It is most used commercial PCM	●Stearic acid melt over a wide range of temperature and have a large variation in latent heat of fusion	●Oldest and most studied. ●Its alloys of inorganic salts and water	●Not seriously consider, due to weight penalty.	●Composition of two or more components. ●Melts and freeze without segregation
Cost	Expensive	2~3 times costly than Paraffin	Low cost	Costly	Costly
Advantages	●No tendency to segregate and to supercool. ●No corrosive ●Chemically stable. ●High latent heat capacity. ●Compatible with metal containers and constriction containers ●Thermal reliability in long run (freeze melt cycle)	●Sharper melting temperature ●Chemically stable. ●No tendency to segregate and to supercool. ●High latent heat capacity. ●Compatible with metal containers and constriction containers ●Thermal reliability in long run (freeze melt cycle)	●Easy availability. ●Sharpe melting temperature ●High thermal conductivity ●Low volume change than others ●Higher density ●Non-flammable ●Compatible with plastic materials	●High Latent heat capacity per unit volume ●High conductivity	●High latent heat capacity per unit volume. ●High conductivity. ●Sharper melting temperature

Disadvantages	●Low thermal conductivity. ●Do not have sharp well-defined melting temperature. ●Flammable ●High volume change during the phase change process ●Non compatible with plastic materials	●Mildly corrosive ●Flammable, should not exposed to excessively high temperature, flames or oxidizing agents. ●Non compatible with plastic materials	●Supercooling ●Phase segregation ●Non compatible with most metal containers ●Thermal performance loss after long run ●Corrosion on metal container. ●Due to higher density, salts settles down at bottom and reduce active volume	● Low Latent heat capacity per unit weight for most materials. ●Low specific heat	●Low latent heat capacity unit weight ●Suffering from surpooling for some materials
Examples suitable in building application (Melting temperature, Latent heat capacity)	n-Pentadecane ($C_{15}H_{32}$) (10, 207) n- Hexadecane ($C_{16}H_{34}$) (18.2, 238) n-Heptadecane ($C_{17}H_{36}$) (22, 215) n-Octadecane ($C_{18}H_{38}$) (28.2, 245) n-Nonadecane ($C_{19}H_{40}$) (31.9, 222)	Propyl palmiate (10, 186); Caprylic acid (16.3, 184) D-Lattic acid (26, 184) Methyl palmitate (29, 194) Capric acid (29, 205)	K_2HPO_4 $6H_2O$ (14, 109) KF $4H_2O$ (18, 330) $FeBr_3 \cdot 6H_2O$ (21, 105) $LiBO_2$ $8H_2O$ (25.7, 289) $LiNO_3$ $2H_2O$ (30, 296)	Cesium (28.65, 16.4) Gallium (30, 80.3) Rubidium (38.8, 25.7)	$C_5H_5C_6H_5$ (26.5%) + $(C_6H_5)_2O$ (73.5%) (12, 97.9) $Ca(NO_3)$ $4H_2O$(47%)+ $Mg(NO_3)_3$ $6H_2O$ (53%) (30, 136) Caprictlauric (61.5%) + acid (38.5%) (19.1, 132) $C_{14}H_{28}O_2$ (34%) + $C_{10}H_{20}O_2$ (66%) (24, 147.7)

2.2.2 PCMs suitable for building envelopes

Each kind PCMs has its typical range of melting temperature and its range of melting enthalpy. The paraffin waxes, salt hydrates, fatty acids and eutectic organic/non-organic compounds are the most used since last 30 years. The relationship between the melting enthalpy (kJ/L) and the temperature of PCM is shown in Figure 2-3. These characteristics are considered very important especially for their application in building envelopes.

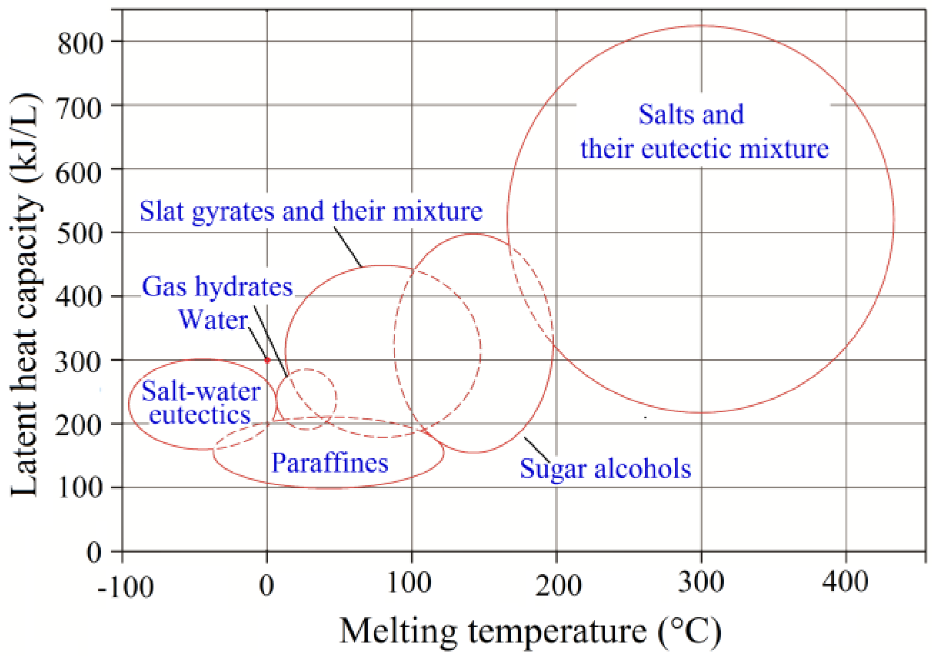


Figure 2-3 Relationship between PCM melting enthalpy and temperature for the different groups of PCM

However, PCM can be applied to building envelopes to reduce the energy consumption and improve indoor conformable level, the melting temperature of PCMs should be not beyond the range of 10~30 ℃. Some of organic, inorganic and eutectic PCMs suitable for building applications are listed in Figures 2-4~Figure 2-6. Figure 2-7 displays that latent heat capacity per unit mass of commercial PCM provided by four PCM production companies with the melting temperature in the range of 10~40 ℃.

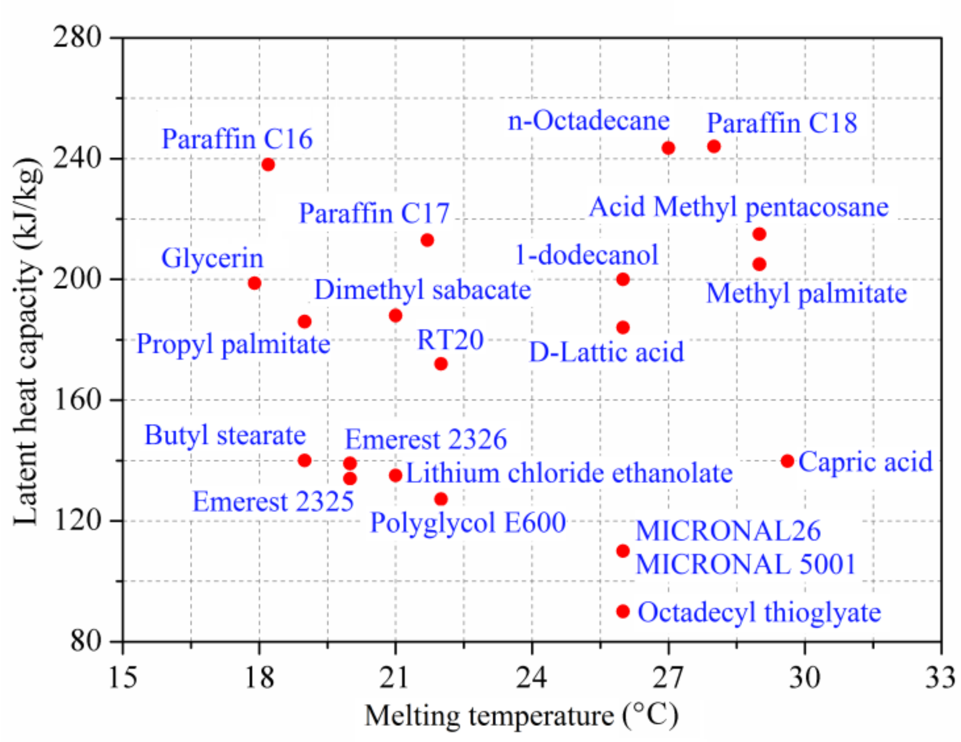


Figure 2-4 Melting temperature and latent heat capacity of some organic PCM

(including paraffin and fatty acids)

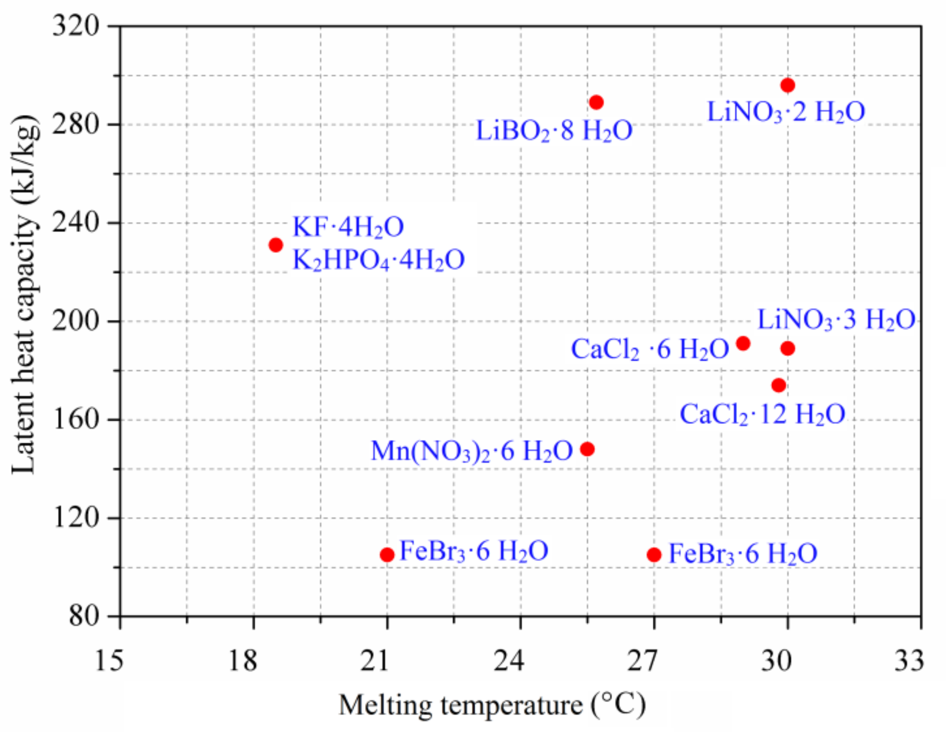


Figure 2-5 Melting temperature and latent heat capacity of some salt hydrates PCM

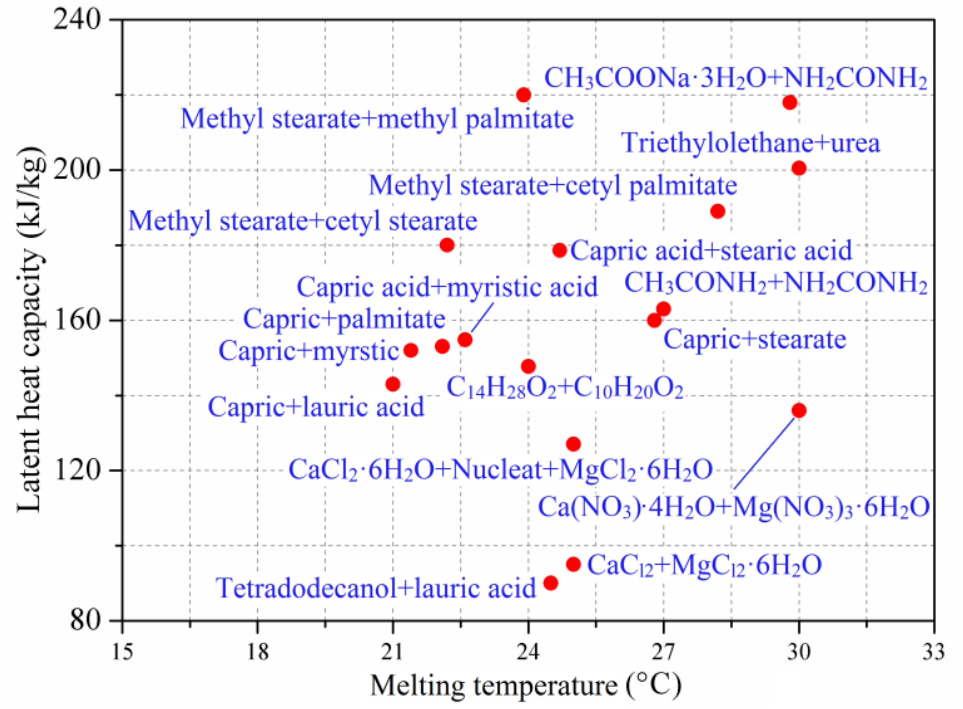


Figure 2-6 Melting temperature and latent heat capacity of some eutectic PCM

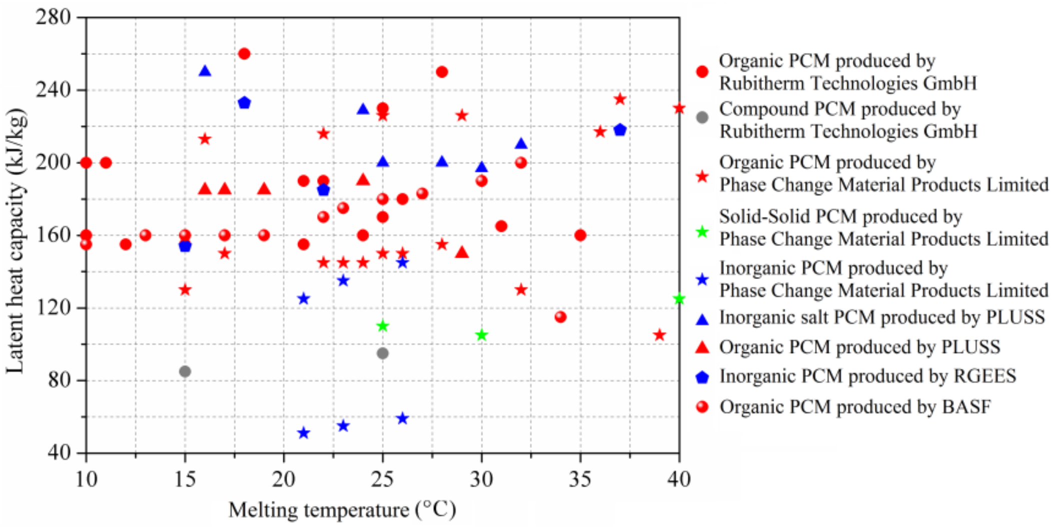


Figure 2-7 Melting temperature and latent heat capacity of the commercial PCM[21,22,23,24,25,26,27]

2.2.3 Selection criteria for the PCM suitable to building envelopes

In order to obtain the suitable application of PCM for building envelopes, it must be comprehensively considered about thermophysical, kinetic, chemical, economic and environmental properties of PCM. The main criteria for selecting PCM are summarized in Table 2-2. Meanwhile it is no doubt that no PCM can have all the desirable properties. Therefore, the choice of a PCM for a given thermal energy storage application in buildings require careful examination of the thermo-physical, kinetic, chemical, economic and environmental properties of the various available candidates, comparing their merits and demerits and in some cases achieving a certain degree of compromise.

Table 2-2 Selection criteria for PCMs suitable to building envelopes

Thermal-physical properties	● Phase change temperature suitable for building application ● High latent heat capacity per unit volume ● High thermal conductivity and high specific heat ● Small volume change and small vapor pressure ● Thermally reliable
Kinetic properties	● High nucleation rate to avoid super cooling ● High crystallization rate to meet demands of heat recovery
Chemical properties	● Complete reversible melt/freeze cycles ● Long-term chemical stability ●Non-corrosiveness and chemical capability with construction materials ● Non-toxic, non-flammable and non-explosive
Economic properties	● Effective cost ● Commercially available (abundant and available.)
Environmental properties	● Low environmental impact and non-polluting ● Low embodied energy ●Separation facility from the other materials and high recycling potential

2.2.4 Incorporation methods of PCM into building wall

At present, the main incorporation methods of PCMs into building wall are the direct incorporation, immersion, encapsulation including microencapsulation and macroencapsulation, shape-stabilization and form-stable composite PCM with the certain supporting material by use of diatomite, expanded perlite, expanded graphite, silica fume, kaolin and granulated blast furnace slag. Table 2-3 compares the characteristics of the different incorporation methods of PCM into building wall.

Table 2-3 A comparison on the characteristics of the different incorporation methods of PCM into building wall.

methods	Advantages	Disadvantages
Direct incorporation	● Simpleness ● Practicability ● Low cost	● Easy interaction with the hydration process and hydration products for some PCMs ● Low bonding between the paste and the aggregate for some PCMs ● Low mechanical properties of the construction materials ● Low the durability properties ● Low thermal stability and reliability ● Low chemical stability ● Easy leakage of PCM
Immersion	● Simpleness ● Practicability ● Low cost	● Low thermal stability and reliability ● Low chemical stability ● Low the durability properties ● Easy leakage of PCM
Encapsulation -microencapsulation	● Non-leakage of PCM during phase transition ● High heat transfer rate ● Small volume change ●High chemical stability ● High stability and reliability ● Low phase separation to microscopic distances ● Non-leakage of PCM	● Low heat transfer rate ● High investment cost ● Low mechanical properties of the construction materials
Encapsulation macroencapsulation	● Easy to ship and handle. ● The intended design	● Low thermal conductivity. ● Easy damage

	● High compatibility of PCM ● Small volume change ● High chemical stability ● High stability and reliability ● Non-leakage of PCM	● More work for integration ● Affinity towards solidification at the corners and edges
Shape-stabilization	● Large apparent specific heat. ● Appropriate thermal conductivity ● High shape stabilization ● High thermal reliability ● No need for container. ● High mass proportion of PCM ●Non-leakage of PCM	● No published
Form-stable composite PCM	● High the retention capacity ● High chemical reliability in long run ● High thermal storage capacity ● High thermal reliability and stability in long run ● Various weight percentage of 5-80% ●Good interaction between PCM and supporting materials ●Non-leakage of PCM ● No need for container.	● No published

2.3 Development of PCMs application in buildings wall

Present day, PCMs are mostly used in buildings light-weight envelops construction for more thermal storage to improving indoor thermal comfort because it can offer higher per unit heat storage capacity than conventional building materials. The capabilities of incorporating PCM in structures is thermally stabilize interior space and shift peak-hour cooling loads. Because of the improved thermal performance gained from PCM incorporation, lighter and thinner building envelopes can be designed and constructed to take full advantage of the performance.

Initial PCM testing in whole-building conditions took place about 70 years ago. That is a residential house with PCMs for passive solar heating built in 1948 by Dr. Maria Telkes.[30] This house is in Dover, Massachusetts, USA. And it contained about 4m^3 of Glauber's salts, which were packed in steel drums located in the southern glazed sun spaces that were ventilated with fans to move the warm air into the living space during the winter. In summer the same system delivered cool air to the rooms. This system alone could keep the house warm for approximately 11 sunless days.

Generations of passive solar walls containing PCM have been studied for decades as a way of heating buildings from a renewable energy source. The key advantages of these walls is their thermal storage capacity. However, when PCM replaced the traditional heavy-weight thermal mall, the solar thermal storage capacity can be increased obviously. And this wall system is called PCM-Enhance trombe wall, as shown in Figure 2-8. Experiments of Glauber's salt in a south facing Trombe wall was done by Swet ,Ghoneim et, and Chandra et al during 1980~1985[31-33]. Los Alamos National Laboratory[34], USA in 1983 carried out a series of field test which used to validate the numerical model which demonstrated that a Trombe wall with PCM was more efficient than conventional concrete walls.

In 1996, Stritih and Novak[35] investigated a passive solar wall. The stored heat using for apace heating with efficiency close to 79%. And got the optimum thickness of paraffinic heat storage and melting point of PCM.

In 1999, Buddhi and Sharma[36] measured the transmittance of solar radiation through a solar storage wall containing stearic acid. This parametric analysis was performed at different melting temperatures and wall thicknesses.

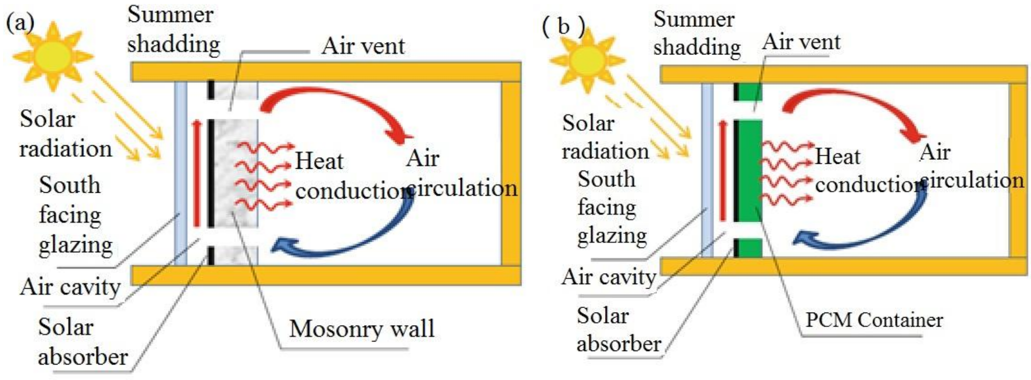


Figure 2-8 Schematics of (a) conventional Trombe Wall and (b) PCM-enhanced Trombe Wall

Except PCM-enhanced Trombe Wall, the concrete block with PCM are also been researched by Lee et al in 2000[37]. He proposed a simplest PCM-enhancement method consists of impregnation of the concrete block with PCM in a constant volume liquid PCM. Which can be applied to different PCM transition temperatures. Concrete is a common construction material made of four components: cement, water, aggregates, and additives. PCM can be either introduced to concrete as an additive or during the impregnation process.

In the research by van Haaren (2012)[38], the introduction of PCMs into the concrete was achieved in two different ways: (1) The sand from a standard mixture was replaced by PCM particles and (2) porous lightweight aggregates were impregnated with PCM and later a concrete mix was made with use of impregnated and not impregnated lightweight aggregates.

Recently, most studies focus on PCM-Enhanced Gypsum Board and Interior Plaster Products. The reason is that PCM with a melting temperature between 19 ℃ and 24 ℃ can be used with best results, since this is a temperature range, which is close to human comfort level in interior environments. The inner surface of building envelops are always considered the best locations for the PCM with gypsum board and plaster used to stabilize building indoor temperature as shown in Figure 2-9. During the past decades years, interest has increased toward the energy saving potential achieved when combining PCM into wall or ceiling interior finish materials. According to many authors, the PCM used on wall surfaces may decrease overheating in interior spaces and reduce energy consumption. In 2006, Kissock and Limas[39] made a numerical and experimental research to verified the effect of PCM on reducing heat loads through the building envelope and proposed a strategy for the location of PCM. The PCM in this study was paraffin octadecane and its melting temperature is 35.6 ℃. At the same year, Shi lei[40] et al. analyzed the wallboards with incorporated organic PCM. Capric acid and lauric acid were used in building wallboards for low-temperature latent heat storage. In the full-scale experiments, it was found that the PCM wallboard room could greatly reduce the energy cost of HVAC systems and notable shift electric power peak load.

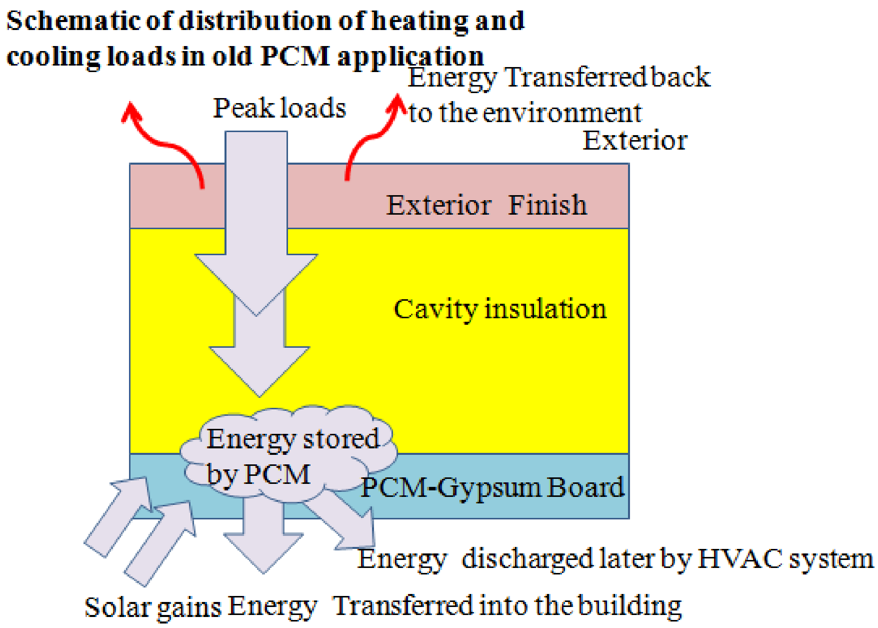


Figure 2-9 PCM as part of the interior surface of the building envelope

In 2002/2003, Kośny and Yarbrough [41,42] proposed another PCM application concept, namely incorporating PCM thermal insulation into internal cavity of lightweight framed walls. It seams unreasonable because it restrains energy transportation between the PCM and the conditioned space and the exterior environment by Khudhair and Farid. However, this PCM location controls the temperature of building walls and thus influences the whole heat exchange.

In 2005, Zhang[43] developed a wood-frame wall integrated with a PCM. Experiments shows that the PCM wall reduced wall peak hex flux by 38%. During the experimental time of several days, the average wall peak heat flux decrease was about 15% and space cooling load decrease was about 8.6% for a 10% concentration of PCM.

In 2009, the dynamic hot-box experiment was done on the wood framed wall with PCM enhanced fiberglass insulation which was joint developed by ORNL, Johns Manville and Microtek Labs[44]. Averagely, the PCM part of the wall has more than 50% reduction of heat flow during the first two hours after the rapid heating process. The load reduction for entire experimental period was close to 20%.

In 2010, Evers [45] made study on the incorporation of PCM-enhanced cellulose insulation for energy consumption saving in buildings. Paraffin-based products and hydrated salt, were mixed into loose-fill cellulose insulation with 10 and 20 % by weight. Results show that the paraffin-based PCM-enhanced insulation reduced the average peak heat flux by up to 9.2 % and reduced the average total “daily” heat flow up to 1.2 %.

2.4 Research status of PCM in building in Japan

As one of the developed country, Japan has the responsibility for reducing GHG emission with a target of 26% CO2 emission reduction in 2030 compared with that in 2013. Of which, the residential buildings sector should reduce 40% CO2 emission reduction in 2030. Many Japanese buildings are wood structure since ancient times, high temperature and humidity. Wood structures are always small thermal capacity and for make sure a high thermal storage capacity, always thermal storage materials such as concrete is used on building envelops such as walls, floors and ceilings. However, these materials has a obviously increase of building self-weight with sensible thermal storage capacity. So many Japanese researchers began to make research on building envelops with PCM as a passive energy saving methods. Most of research are that PCM materials is mixed with other building materials. However, it is also under experimental period and have not been applied in a large scale.

2.4.1 Research stature of PCM in building envelops in Japan

Japan Testing Center for Construction Materials makes a series research on performance evaluation method of PCM in 2013. This research contains five parts: Test methods of thermo physical property (outward appearance specific heat); Test methods of apparent specific heat and heat reserving volume, Inspection in the experiment house, Measurement conditions of apparent specific heat, specific heat sink radiate heat of PCM.[46-50]

Dr. Takeshi KONDO et [51,52] of Department of architecture, Tokyo university made study on the thermal storage of PCM wallboard and make the measurements of thermal behavior and the effect on indoor environment in Tokyo in 2001. At first, by using the PCM-wallboard to a wooden house which PCM was installed in the wall and ceiling with a 69.5% area. The melting point of PCM is 25 ^{o}C and thickness was 12mm. Figure 2-10 is the appearance of experimental buildings. Results found that the house with PCM wallboard have a maximum 10 ^{o}C decrease in March. However, because indoor temperature was higher than the PCM melting point in August, there were no temperature deduction. For standard deviation of indoor temperature, house with PCM had about 40%~80% reduction which could make sure the indoor temperature flat effect. According to simulation model verified by experimental model, thermal performance of three wood wall structure with PCM layer (as shown in Figure 2-11) were analyzed under Tokyo climate. Compared with RC wall structure, wood wall with PCM layer (24mm) can resistant temperature value of 1.5 ^{O}C and reduced about 70% thermal energy compared with that of wooden wall.

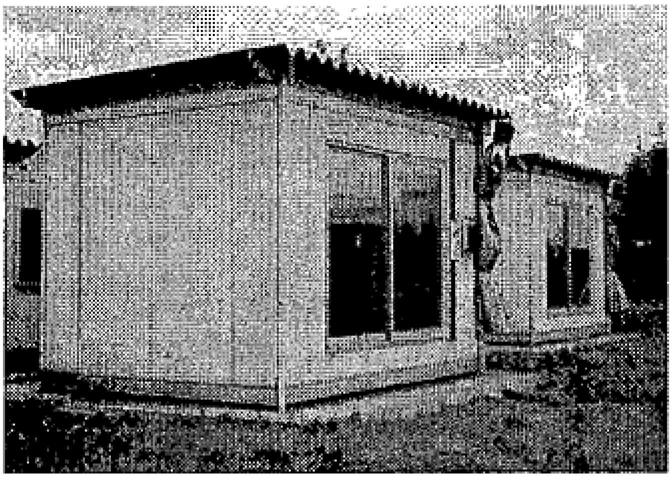


Figure 2-10 The appearance of experimental buildings (left: with PCM; right: without PCM)

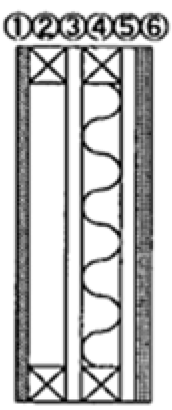
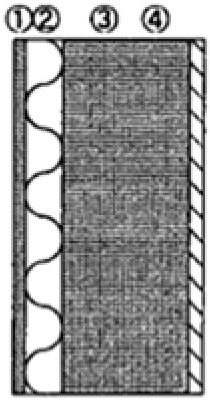
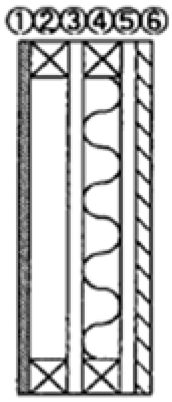
Wood wall with PCM	RC	Wooden wall
		
①Sliding 9mm ②Air layer 30mm ③Plywood 12mm ④Insulation materials 30mm ⑤Plywood 12mm ⑥PCM layer 12mm	①Sliding 9mm ②Insulation materials 30mm ③Concrete 100mm (150mm, 200mm) ④Gypsum wallboard 12mm	①Sliding 9mm ②Air layer 30mm ③Plywood 12mm ④Insulation materials 30mm ⑤Plywood 12mm ④Gypsum wallboard 12mm

Figure 2-11 Three kinds wall structure

Hiroshi TAKEDA[53] of Tokyo university of science made research on application of phase change materials (PCM) to building heating, verification of room temperature fluctuation constructed by wall with built-in PCM bag. Theory calculation methods was obtained using finite method and response factor method. And the calculated value is well according to experimental value. The melting temperature in experiment is 20 ^{o}C. Results showed that under Tokyo climate condition, the heat and cold load of house with PCM (yearly heat load:58707MJ, cool load 201355 MJ) is obviously lower than that of house without PCM (yearly heat load:45756MJ, cool load 200473 MJ), as shown in Figure 2-12. The time of phase change status had intimate connection with indoor setup temperature.

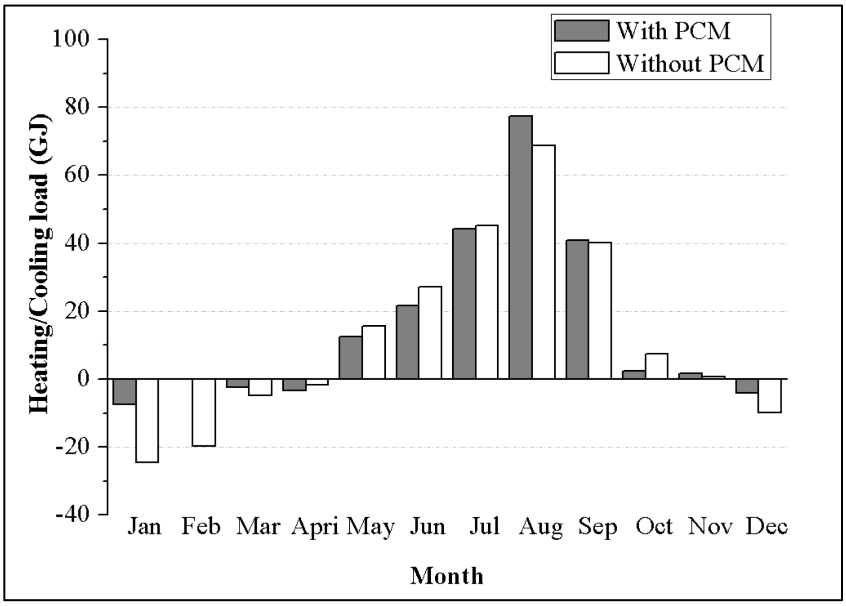


Figure 2-12 Comparison of monthly heating/cooling load between house with PCM and without PCM

Yuki SATO [54] of Daiken CO., R&D center made research on the reduction effect of the space heating load by installing PCM on interior building walls by a model box experiment, a test house experiment, and a numerical simulation under Tokyo climate. The heating load during the night was reduced by up to 9.6% in sunny day by apparent effects of heat storage on PCM constructed in the floor of test house. In addition ,the horizontal distribution of room temperature was moderated by relieving cold drafts from windows with temperature rise of the PCM constructed floor in the outdoor experiments. Sensitive analyses on the heating load for a single-family house utilizing THERB and multiple linear regression analyses with calculation results clarified that the construction area of PCM, the temperature difference between melting point of PCM and heating preset temperature. Figure 2-13 showed that the more PCM utilized, the bigger heating load reduction. Figure 2-14 and 2-15 showed that when the peak melting temperature was same with indoor heating preset temperature 20 ^{O}C, PCM melting range was the smallest (2 ^{O}C), the effect of heating load reduction is best.

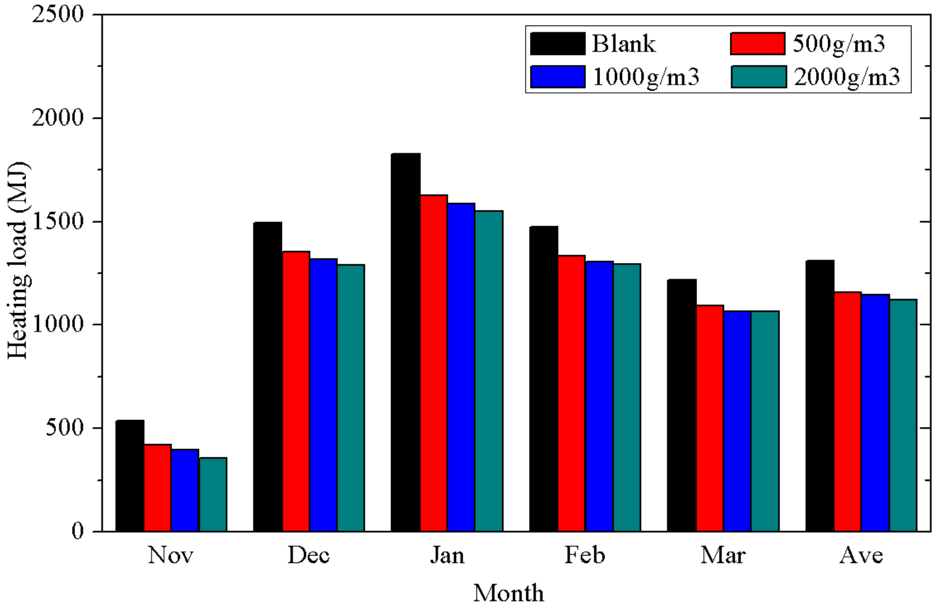


Figure 2-13 Relationship between heating load and the weight of PCM

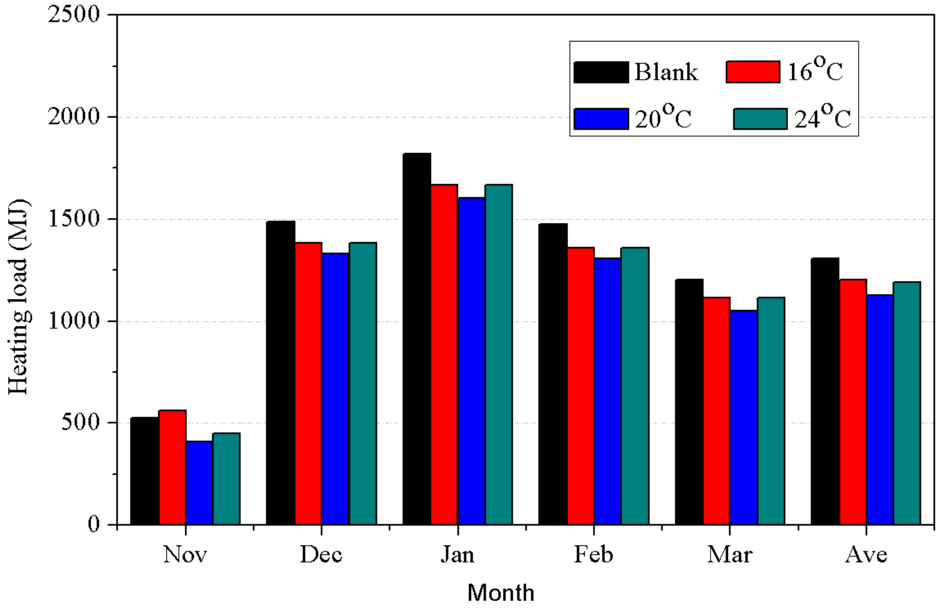


Figure 2-14 Relationship between heating load and PCM peak melting temperature

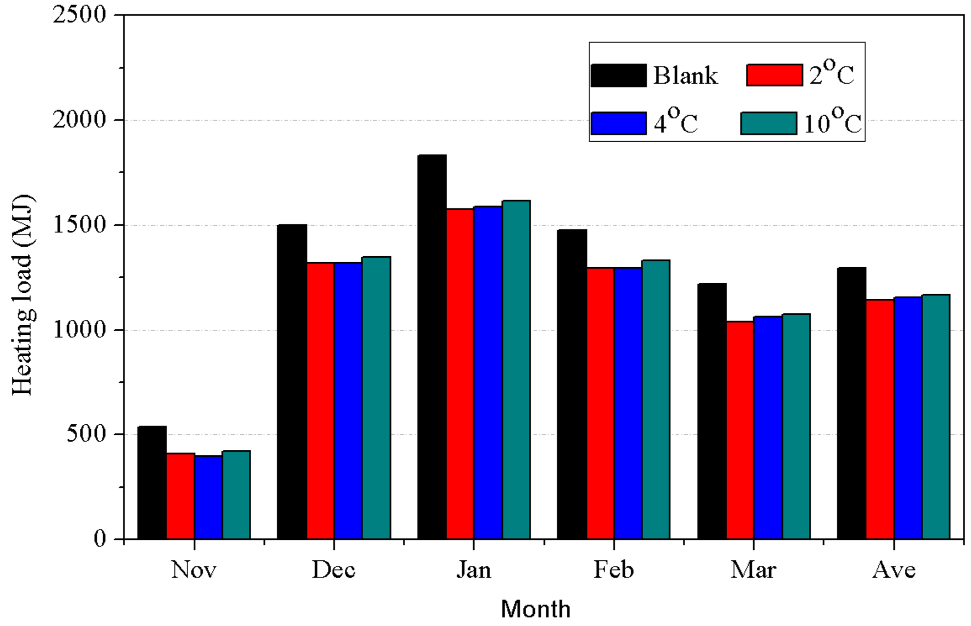


Figure 2-15 Relationship between heating load and PCM melting range

Dr. SOEDA Haruo et of Department of Mechanical Science, Osaka University make series study on indoor thermal environments control with phase change materials.[55,56] Their research is divided into three parts. In part I, a numerical model of PCM dealing with its melting-freezing process was introduced and its performance was examined comparing with some theoretical and numerical results. Author developed a PCM numerical model incorporated into a CFD code to investigate the effect of PCM wallboard on the indoor thermal performance. Figure 2-16 is the research object. Analysis were made on floor and wall respectively with or without PCM layer which its solidus temperature and liquidus temperature were set as 27.8 and 36.2 ^{O}C.

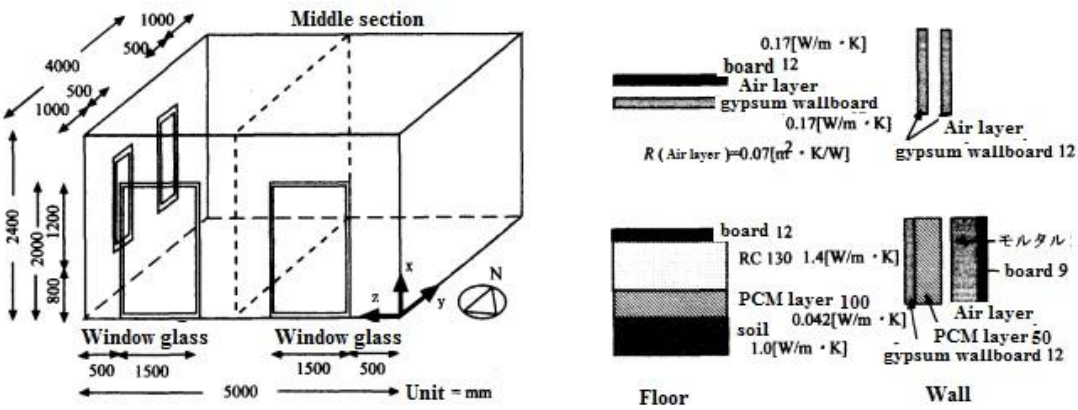


Figure 2-16 Research object

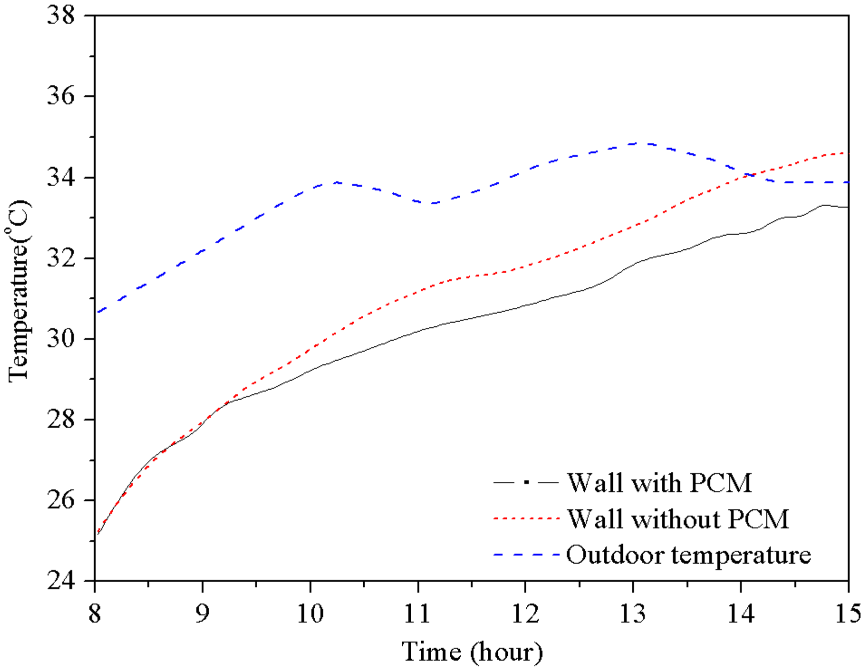


Figure 2-17 Comparison of average indoor air temperature when wall with PCM and without PCM （11th August）

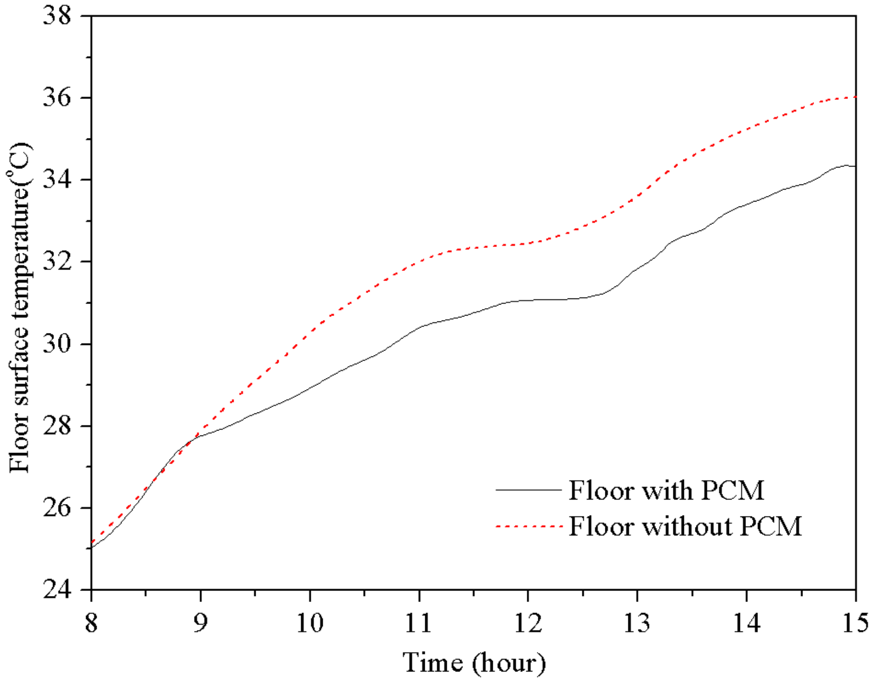


Figure 2-18 Comparison of average indoor floor surface temperature when floor with PCM and without PCM（11th August）

Under the climate of Osaka (August 11), the simulation comparison result of wall with and without PCM layer (Figure 2-17) and floor with and without PCM layer is obtained (Figure 2-18). It could be found, under summer climate condition, the room with PCM in envelops has a lower indoor air temperature and better thermal comfort. The reduction of temperature for indoor air temperature and floor surface temperature is about 1 ^{o}C.

The part 2 of this series is experiment of thermal conduction with phase change of paraffin and numerical validation of PCM Model. The part 3 is evaluation of reduction in energy consumption and improvement of thermal comfort of PCM wallboards for summer and winter using a Japanese standard house with two floors using numerical simulation under Osaka climate. The area of PCM layer is 439 m2. The solid ratio and PMV value in summer in different area were compared. As a result, in summer the maximum wall surface temperature reduction value is 1.5 ^{o}C in summer and 1.3 ^{o}C in winter. The indoor comfort has also been improve because of PCM in Osaka. In addition, energy consumption of air-conditioner in the rooms with PCM wallboards were reduced by 1.4% and 1.2% respectively in Tokyo and Osaka, compared to conventional gypsum boards. In summer, all area has electric consumption reduction, 1.4% in Tokyo and 1.2% in Osaka. However, in winter, the electric consumption has increased in cold area. Such as in Sapporo, the increase value is 1.0%. In Tokyo and Osaka, the value is decreased with 0.6% and 0.2%, which is smaller than that of summer. The biggest energy saving effect is in Kagoshima with the value 4.1%.

2.4.2 Research status of PCM in air-conditioning system in Japan

Katsunori NAGANO [57-59] of Hokkaido University made series study on floor supply air conditioning system storing cold energy for building structure and granules including phase change material. The published paper were divided into three parts. Part 1 proposed a new floor supply air conditioning system (Figure 2-19), in which thermal capacity was augmented by latent heat storage compared to general building structure energy storage. An experimental apparatus is constructed for test the system. The PCM which showed phase change is around 20 ^{o}C was made of foamed glass beads and paraffin waxes. The measurements results showed that 89% of daily cooling load could be stored in the thermal energy storage period during night under a condition with a 30mm thick packed bed of the PCM granules in office buildings. The part 2 is a computer simulation calculation (the model is shown in Figure 2-20) for the air conditioning system in office buildings under Tokyo climate. Results showed that daily air conditioner load can be completely shifted to the period for thermal energy storage during night when the available enthalpy difference of granules including PCM is 128.5 kJ/kg. The part 3 is utilization of micro-capsule pellet PCM and evaluation of thermal environment. The PCM used in this part was bigger than that of before. Experiments was made for comparing the outer surface connective heat transfer coefficient. Then simulation was made for the evaluation of thermal environment. Result shows that air-conditioning cold load shifting effect can be determined by temperature conditions in the nighttime and daytime. The effect of radiation from the floor face allows the set temperature to be increased to 28 ^{o}C by using a FMC-PCM which shows phase change around 20 to 23 ^{o}C. Thermal sensation indexes indicate the comfortable sensation under a condition with it. The use of the FMC-PCM also effects the improvement of the uncomfortable coldness in the morning in usual systems.

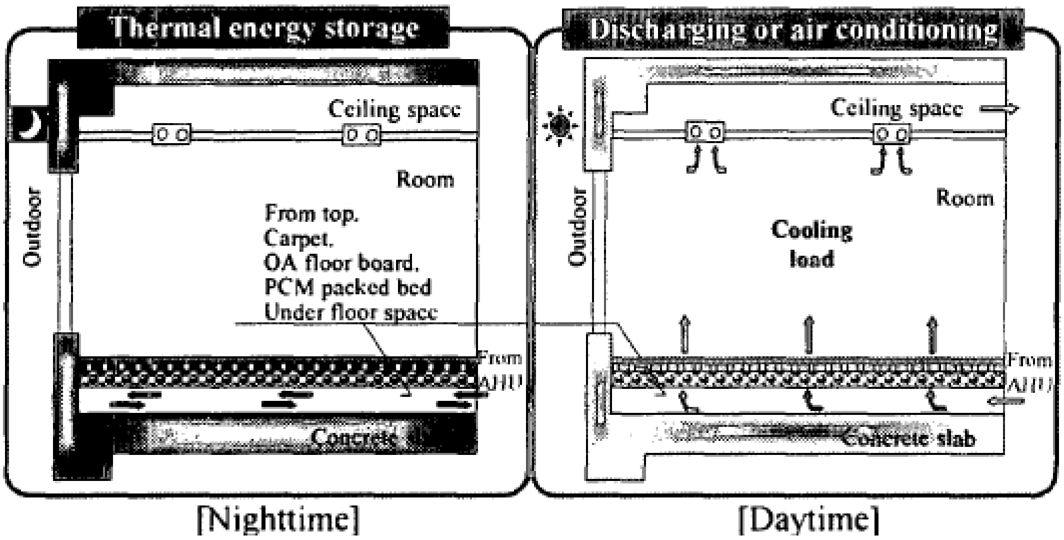


Figure 2-19 Concept of air-conditioning system

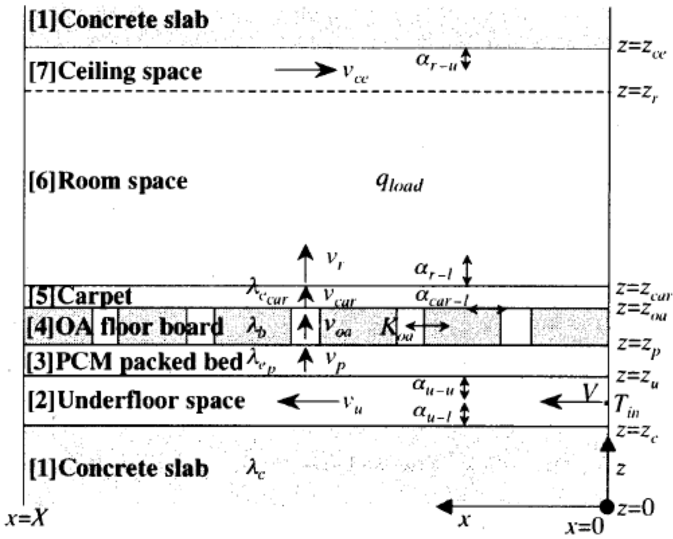


Figure 2-20 Section of subject for the computer simulation model

Yuka Kusama[60] made study on the efficiency of thermal storage for wall heating-cooling system with PCM. Energy consumption of three house in Sapporo including an office(N-project), resident (H-project) and model house installed PCM bag on building walls were tested. The floor area of the three house was separately 104.8m2, 102.89m2, 124.94m2. The weight of PCM in each house is 117kg, 108kg and 99kg. Research result shows that houses with PCM layer can reduced heat load obviously, however, whether the PCM layer was installed on the top or down of the wall influenced the energy storage effect significantly. Radiation cooling and heating house system with PCM that the supply water temperature is 30 ^{o}C, the indoor temperature fluctuation could reduce 2 ^{o}C. Difference of Heat lose coefficient of experimental value and calculation value was very small, so the energy saving method using PCM could be sure.

Takuji Nakamura[61] made a evaluation on energy and thermal characteristics of the building thermal mass storage system based on the floor-supply displacement air-conditioning system with the granulated PCM (Phase Change Material). A typical commercial building model is simulated by a computer and the influence of the quantity of the PCM and the rate of the supply air into the room at the thermal charging period is examined. This simulation consider that the peak-cut is carried out by the PCM quantity smaller than the case of all cooling load supplied by the thermal storage. And the efficiency of the peak-cut, the thermal storage quantity of the each materials and the effect of the thermal environment improvement by the PCM is studied. And the energy evaluation of the air-conditioning system shows that the energy consumption is reduced by optimizing the thermal charging time all over cooling season. Figure 2-21 is the floor-supply displacement air-conditioning system with PCM. Figure 2-22 is the Relationship between indoor temperature and PCM quality.

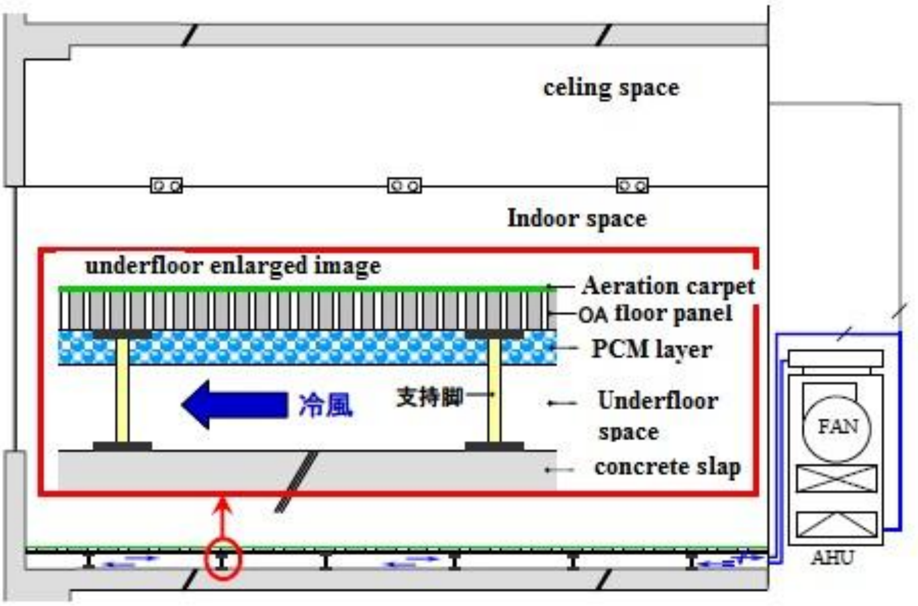


Figure 2-21 Floor-supply displacement air-conditioning system with PCM

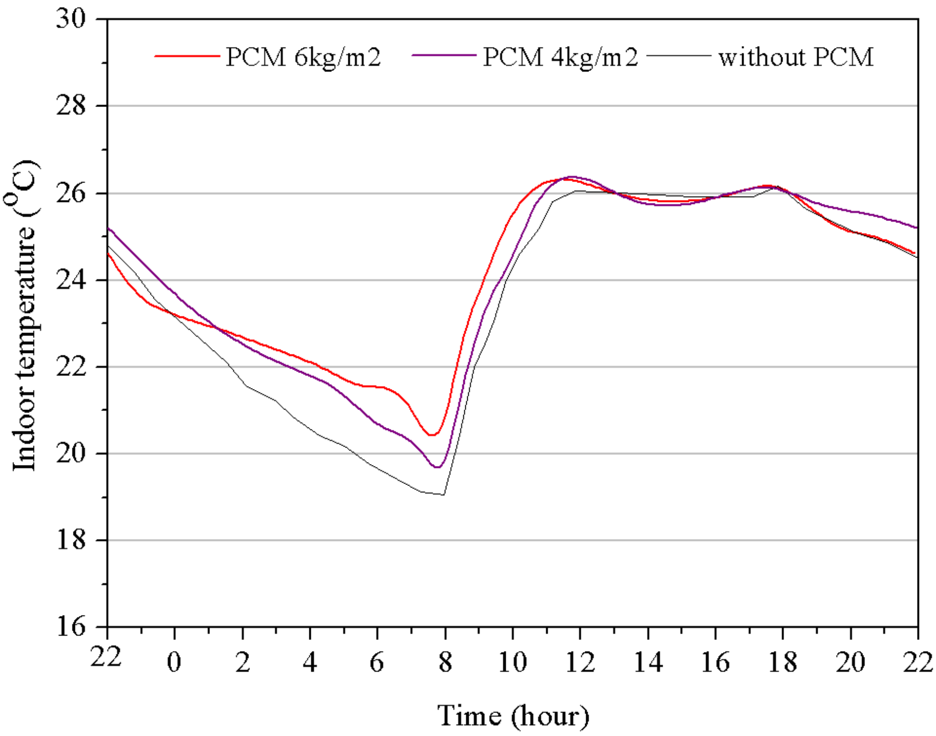


Figure 2-22 Relationship between indoor temperature and PCM quality

Hiroki KAWASHIMA[62] of university of Tokyo made study on the passive solar heating design of residential buildings with adaptable time rate estimation. And the PCM thermal storage performance was tested using indoor experiment model and man-made sunlight source. Then the outdoor experimental was carried out for real house in Tokyo. At last, a numerical model to simulate the room air temperature with PCM was proposed. And using southern window area to Q value charts with adaptable time rate estimation as a evaluation method for find the better combination among heat gain, heat loss, thermal mass and thermal mass area. Hisataka KITORA[63] made study on building thermal mass storage system with granulated phase change material using to the conventional under-floor air distribution system by simulation.

Table 2-4 List of research on PCM in buildings in Japan

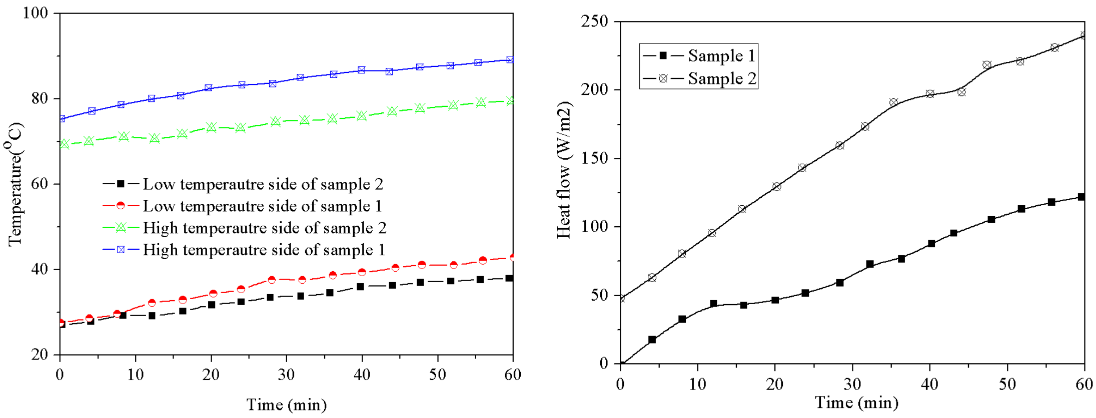
Author	Published Year	Content	Research method
Takeshi Kondo of Tokyo university	2001	Thermal storage of PCM wallboard; its thermal behavior and effect on indoor environment; location : Tokyo	Outdoor experiment and simulation
SOEDA Haruo of Osaka University	2004	Indoor thermal environments control with Phase Change Materials; Location: Sapporo, Aomori, Sendai, Tokyo, Osaka, Fukuoka, Kagoshima	Experiment under Osaka climate and Simulation using CFD
Katsunori NAGANO of Hokkaido University	2004	Floor supply air conditioning system storing cold energy for building structure and granules including PCM under Tokyo climate	Indoor small-scale experiment and theory calculation
Hisataka KITORA	2009	A Study on Building Thermal Mass Storage System with Granulated PCM using to the conventional under-floor air distribution system	simulation
Takuji Nakamura	2010	evaluation on energy and thermal characteristics of the building thermal mass storage system based on the floor-supply displacement air-conditioning system with the granulated PCM	Simulation using the CFD
Yuki SATO of Daiken CO., R&D center	2012	The reduction effect of the space heating load by installing PCM on interior building walls under Tokyo climate	Indoor and outdoor experiment and simulation using THERB for HAM
Yuka Kusama of Hokkaido University	2012	The efficiency of thermal storage for wall heating-cooling system with PCM bag on building walls in three house in Sapporo including an office(N-project), resident (H-project) and model house	Experiment
Japan testing center for construction material	2013	Performance evaluation method of PCM properties	Indoor experiment
Hiroki KAWASHIMA of the university of Tokyo	2014	study on passive solar heating design of residential buildings with adaptable time rate estimation under Tokyo climate	experiment and simulation

2.5 Research status of PCM in building in China

The application of PCM in buildings in china could be divided in building walls, floor heat storage system and air-conditioning systems.

2.5.1 Research status of PCM in building walls

Yan Quan-ying[64] made study on the thermal performance of cement wall containing phase change materials. Result shows that the surface temperature of phase change wall is lower than that of common wall. The temperature changes more gently and the temperature fluctuation is less. The thermal flow via phase change wall is far less that via common wall, and changes gently. Thermal fluctuation is less and occurs late. The infiltration problem of the wall is not serious when the content of paraffin is less. It is preferable that the content of paraffin is less than 5%.



(a)Temperature (b) Heat flow

Figure 2-23 Law of temperature change and heat flow change of PCM wall and common wall (sample 1 is common wall; sample 2 is PCM wall)

Feng Guo-hui[65] selected two kinds of fatty acid as phase change material and make phase change wallboard, carried on thermal functional analysis of performance of the wallboard taking the climatic conditions into consideration that summer day and night time of northern country. Results shows that putting phase change wallboard into application in cold area of the North can utilize abundant natural cold wind terms of our country northern cities and towns, and this will accord with the policy of national development and reform committee of decreasing price of electricity and electricity for resident of villages and towns, moving peak fill out the valley, it will not only reduce heating investment and energy consumption of air conditioning system, but also will be an effective way for improving negative effect caused by building energy consumption to the environment.

Chen Chao[66] made feasibility study on composite PCM wallboard in passive solar house using experiment and simulation method in Beijing where solar energy resource is abundant in winter based on building thermal physics, heat transfer and phase change storage theories.

ZHANG Zhengsong[67] took Nanjing as the research object, the thermal performance difference between SSPCM panel and EPS panel were compared based on the Matlab program. Furthermore, from the perspective of phase change temperature, the effects of SSPCM panel were analyzed using an enthalpy model. The results showed that the SSPCM panel could improve the summer insulation performance of lightweight wall and reduce the heat through the building envelope simultaneously. In addition, energy storage wallboard of melting temperature 28 ℃ could decrease the indoor cooling load greatly, and the energy-saving effects were obvious.

XU long[68,69] made study on performance of composite PCM adjusting indoor thermal environment of light weight enclosure buildings. Comparison of indoor thermal environment of cabinet rooms with the same size where composite PCM was installed and composite PCM was not installed were compared through experiment. Result showed that in hot summer climate, composite PCM could effectively control fluctuation and rise of indoor air temperature of lightweight envelope buildings; maximum indoor temperature could be reduced to 8.5^{o}C; secondly, in the case where outdoor temperature was low, during the night composite PCM could release its heat received at daytime, and could increase a maximum indoor temperature of 4 ^{o}C; In addition, use of composite PCM could cause energy saving rate of air conditioner to reach 65.34%, maximum energy saving rate of heating could reach 77.27%. Under winter climate, in sunny day climate conditions, PCM could effectively control fluctuation and rise of indoor air temperature of lightweight envelope buildings. Especially at night, maximum indoor temperature could be increased to 8.5 ^{o}C. In cloudy day climate conditions, PCM improve indoor thermal environment very limitedly, only the equivalent of increasing the thickness of the wall. PCM should be used in large solar radiation areas. It can play heat storage and heat release function.

WANG Jun[70] made study on effectiveness of improving tent envelope thermal performance based on PCM using simulation. For the sake of improving thermal performance of tent envelope, composite structure was proposed and applied in tent, including outer fabric layer, phase change material(PCM)layer and inner fabric layer. Meanwhile, the heat transfer model of this new type structure was established and verified. In addition, for the climatic conditions of Chengdu in China, the thermal performance of composite structure was evaluated and effectiveness of improving tent envelope thermal performance based on PCM was determined with the aid of numerical simulation under the influence of different PCM thermophysical properties, containing PCM thermal conductivity coefficient, latent heat, specific heat capacity and phase—transition temperature.

2.5.2 Research status of PCM in floor heating system

Ye Hong[71] applied form-stable PCM as the thermal mass in radiant floor heating system and established theory mathematical model of the system for simulation. Experiment is also done for the system. The results showed that the calculated results agree well with those of the experiments. The floor radiant electric heating system with form-stable PCM had a lower operation cost under keep the same indoor temperature. In addition, because of its better thermal storage capacity, the temperature caused by on-off of the system was smaller.

Deng An-zhong[72] performed the floor radiation heating experiments by using PCM mortar and common mortar separately to obtain the characteristic of charging and discharging latent heat energy of the containing PCM floor and to analyze the indoor temperature distribution. The results showed that PCM mortar as filled materials in floor heating system will improve indoor temperature environment and lower the thickness and load of the floor heating system.

LIN Kongpin [73] developed a model to analyze the thermal performance of an under-floor electric heating system with SSPCM plates. The model was verified with experimental data. Then the effects of various factors on the thermal performance of the heating system was analyzed. The results show that the system should be designed with the proper phase transition temperature and air layer thickness which depend on the specific climate conditions. The indoor temperature can be kept in the comfort range by controlling the heating floor area during the winter.

Xiangfei KONG[74] etc of Tianjin university make an experimental research on the use of phase change materials in perforated brick rooms for cooling storage. The test rooms were located in Tianjin (a middle latitude city in China) in the eastern edge of the Eurasian continent latitude. A new kind of PCM macro encapsulated method, PCM panel, was developed and experimented in two full size rooms; meanwhile, a same size of room without PCM panel was also built to be the reference. PCM panels encapsulating capric acid (CA) were installed on the outside surface in one room and the PCM panels encapsulating the mixture of CA and 1-dodecanol (CADE) with a melting point of 26.5 ^{o}C were used inside building. Figure 2-24 and 2-25 are section of building structure for reference room and PCMIW room. Furthermore, three operation measures, inclusive of free cooling, open window and door at night and forced ventilation at night with a low-power air exhauster, were carried out in experimental process, which occurs in summer. The result has produced the good effect of decreasing temperature peak, reducing temperature fluctuation and increasing the thermal inertia, and indicated the opportunity of PCM panel application.

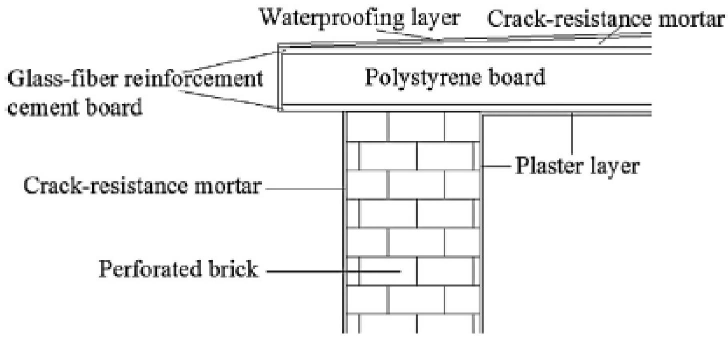


Figure 2-24 Section of building structure for reference room

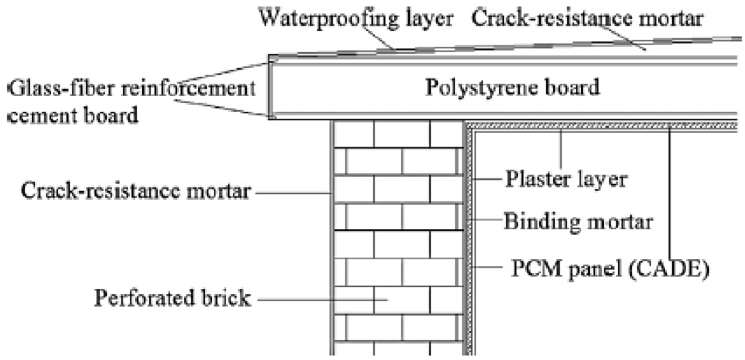


Figure 2-25 Section of the building structure for PCMIW

Chi-ming Lai etc[75] of National Cheng-Kung University, Taiwan make study on thermal performance of an aluminum honeycomb wallboard incorporating microencapsulated PCM by experiment in summer season. The results indicated that the aluminum honeycomb used for structural support and enhancing the thermal conductivity in the prototype rapidly transferred the heat flux into the mPCM. Consequently, the latent heat can be used to increase the time lag of the peak load, effectively shifting the peak hours of electricity use in the summer and achieving a lower module surface temperature than other modules. Thus, the mPCM + honeycomb exhibited better control over the surface temperature, which makes it suitable for use in places where the exterior surface temperature must be controlled. A correlation of the effective thermal protection duration of the mPCM + honeycomb modules for Ste* = 2–5 and Sc* = 0.24–0.32 was proposed.

Xianshi[76] made experimental assessment of position of macro encapsulated phase change material in concrete walls on indoor temperatures and humidity levels. The experimental investigation on macro encapsulated phase change material (PCM) incorporated in concrete walls of room models in real conditions have been done. The effect of positions (externally bonded, laminated within and internally bonded) of macro encapsulated PCM in concrete walls on indoor temperatures and humidity levels of room models was analyzed. Experimental results indicated that

PCM models could adjust the indoor temperature and humility levels, however, its effectiveness was found to be greatly dependent on the position of PCM in concrete walls. The model with PCM laminated within the concrete walls showed the best temperature control and was effective in reducing the maximum temperature by up to $4^{O}C$. Whereas, the model with PCM placed on the inner side of concrete walls showed the best humidity control and reduced the relative humidity by16% more than the control model. Therefore, it can be concluded that PCM models are thermally efficient and by reducing the relative humidity they provide comfortable and healthy indoor environment.

2.6 Summary

In this chapter, the basic properties of PCMs such as characteristics, selection criteria for the PCM suitable to building envelopes, incorporation methods of PCM into building wall are introduced. The development of PCM application in buildings envelops has been investigated. Results shows that PCM in building walls are firstly applied in passive solar wall-PCM enhanced Tromb wall, after that, the application research on concrete block with PCM, PCM-enhanced gypsum board and light-weight wall integrated with PCM are began to be researched. In addition the research status of building integrated with PCM has been investigated from two aspects: application in building walls and application in building heating system in China and Japan.

According to the investigation, the application of PCM in buildings envelop now are under the period of research and experiment in Japan. The real building walls or floor-heating system with PCM is small. Most of research focus on wood structure residential buildings envelops with PCM layer because wood structures’ small thermal capacity. Most research are under Tokyo climate condition.

In china, PCM are always used in light-weight wall, concrete block, and gypsum plaster. And results shows that PCM can increase wall thermal inertia and the increase indoor thermal comfort and save air-conditioning load and heating load.

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Chapter Three: Calculation Method for Confirming PCMs Phase Change Range

3.1 Introduction

3.2 Principle of PCMs Phase Change Range

3.3 Related Inference of The PCM Phase Change Range

3.4 Theory Calculation Method of PCM Phase Change Range

3.5 Factors Influencing PCM Phase Change Range

3.5.1 Effect Rule of Outdoor Climate Condition on PCM Phase Change Range

3.5.2 Effect Rule of Wall Structure on PCM Phase Change Range

3.6 Summery

3.1 Introduction

So far, during the period of selecting buildings envelops energy saving materials, people always focus on their heat material resistance and ignore heat capacity. In fact, selecting big heat capacity materials can improve wall thermal inertia effectively and then improve wall thermal performance. A big heat capacity materials can be achieved by the incorporation of latent heat storage technologies by using PCMs which absorb and release heat in greater amounts than conventional building materials. This is because conventional building materials store heat energy in a sensible method rather than a latent manner. As shown in Figure 3-1, the heat storage capacity of PCMs is 44 times more heat than concrete by using latent heat during phase change period[1]. Figure 3-2 is Example of a Paraffin-based PCM’s specific heat changes during a phase change process[2]. It can be shown that the specific heat of the PCM during solid statue and liquid statue is almost a constant, during the phase change period, the specific heat increases significantly and then decreases back when it completes its phase change. However, for the traditional materials, its specific heat keep almost constant even in phase change period. Which means that much less volume is required to store the same heat in building envelops when PCMs are used instead of conventional building materials.

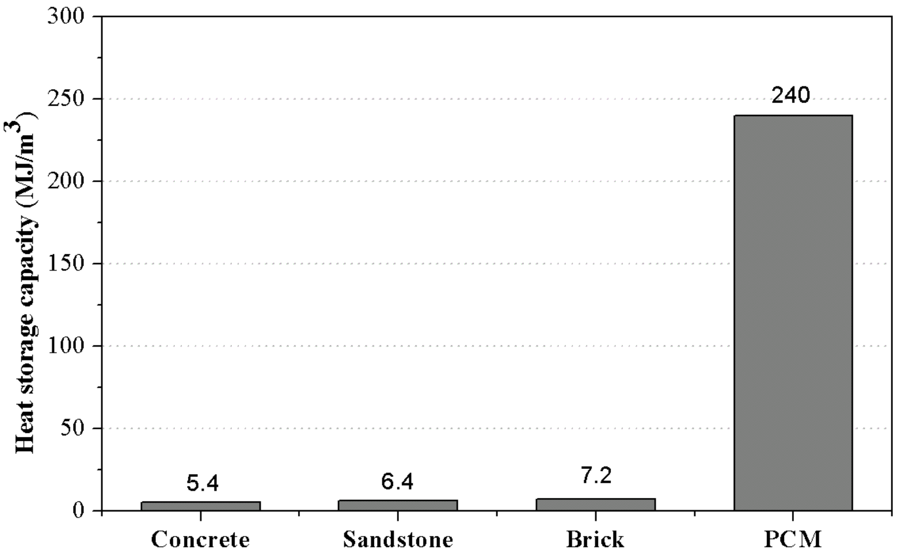


Figure 3-1 Heat Storage Capacity of PCM Compared to Conventional Building Materials

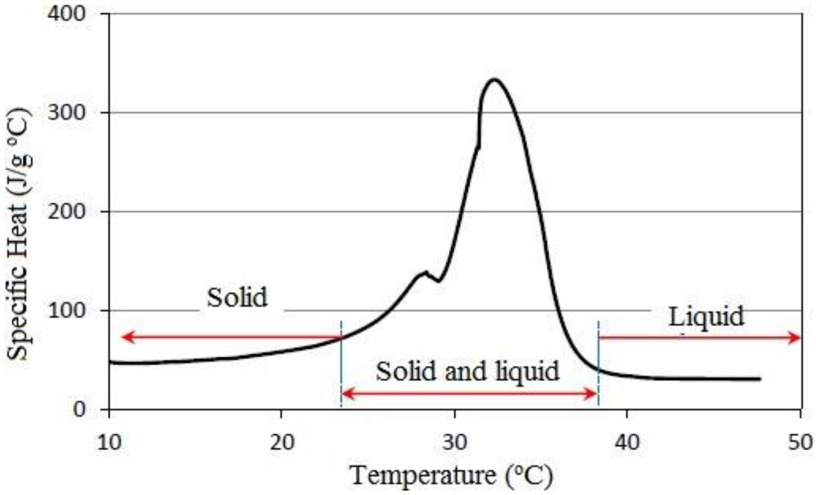


Figure 3-2 Example of a Paraffin-based PCM's specific heat changes during a melting process

In addition, the kinds of PCMs in market vary with different thermal performance parameters, different type integrated with building and heat and cold source, adaptive area. Because each PCM has its own phase change temperature and phase change range, which is the temperature at which latent heat is absorbed or released, it is important to use an appropriate PCM for the purpose of building envelope design because of different outdoor climate conditions, wall type and the location of PCMs.

Many researchers have made research on the application of PCMs in building walls, and everyone knows selecting a proper PCMs is important for the performance of walls. However, nobody have proposed a appropriate method for selecting PCMs for walls under different contidon. If the phase-change temperature range is far away from the temperature change of the PCM layer in building envelopes, PCM would always be solid or liquid without any phase change. Meanwhile, if the phase change temperature range is much bigger than the temperature change of the PCM layer, the part of PCM would have no phase change and the best effect of phase change would not be obtained. In addition, if the phase-change temperature range is much smaller than the temperature change of the PCM layer, PCM will lose the phase change effect owing to the full phase change during the partial period with high or low temperature, when there is often the peak time of electricity consumption for air conditioning or heating. Therefore, it is of great importance to determine the phase-change temperature range for PCMs properly according to envelop structures, indoor and outdoor environment.

The research of Wang et al. shows the phase change temperature range of 12-22 ℃ is a better choice for the prefab house with one polystyrene foam board of 40 mm in the Chengdu city, China[4]. Meng et al. numerically researches the influence of the PCM thermal physical properties on the temperature and the heat flow of inner surface in the Chengdu climates. Their research shows the best phase change temperature range is 14-26 ℃ for the sintered brick wall of 240mm integrating with the PCM layer of 20mm[5].

Although some optimized phase change temperature ranges are proposed for the certain wall under the given climate condition in some published papers, the optimization method is always lacked on phase change temperature range with the consideration of wall structures, indoor and outdoor thermal environment, the PCM thermal physical properties and so on. Only when this main problem is solved could PCM be widely used in building envelops with a high efficiency. In our study, the determination method about the PCM phase-change temperature range is researched based on the theory analysis of heat transfer laws, and the calculation equations are proposed. Meanwhile, all factors influencing the phase change range such as wall structures, thermal environment and PCM thermal physical properties, is analyzed qualitatively in this chapter.

3.2 Principle of the PCM phase change range arrangement

Usually, when PCM is integrated into building envelopes, the phase-change heat storage will be expected in a certain period, which maybe summer, transition season or the whole year. However, no matter under any period, there are high and low temperatures for outdoor thermal environment and the relatively constant temperature for indoor thermal environment owing to air-conditioning and heating. In our study, it is considered that PCM has the efficient phase change heat storage property in the whole year with indoor air temperature of 20 ℃ in winter and 25 ℃ in summer.

Figure 3-3 shows the schematic diagram on wall temperature distribution under the heating in winter and the air-conditioning in summer. The blue layer is the PCM layer in the wall. And the basic principle is shown on the full phase change of PCM in the Figure 3-3. As shown in the Figure, wall temperature always decreases from outside to inside during summer, while wall temperature always increases from outside to inside during the winter.

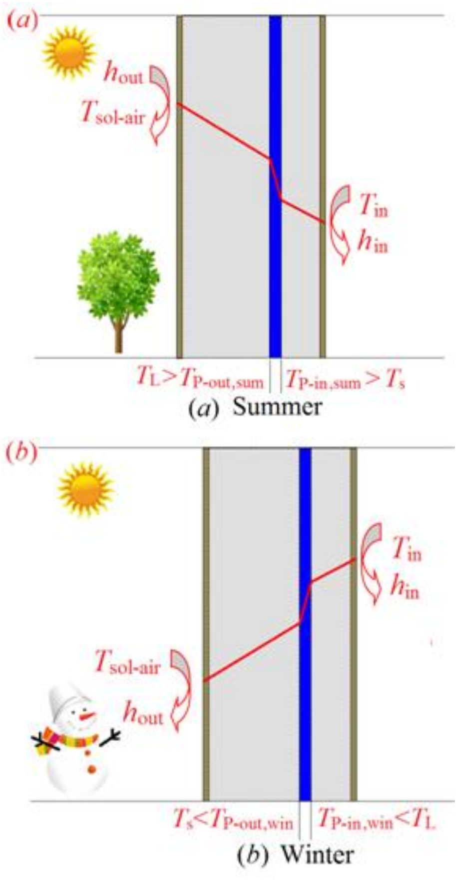


Figure 3-3 The temperature distribution of wall under (a) summer, and (b) winter

Therefore, if the full phase change of PCMs can occur, the PCMs phase-change temperature arrange must be satisfied as follows:

The constraint relationship of the full phase change of PCMs in summer:

$$T_S < T_{\text{P-in,sum}} < T_{\text{P-out,sum}} < T_L \tag{3-1}$$

The constraint relationship of the full phase change of PCMs in winter:

$$T_{\text{S}} < T_{\text{P-out,win}} < T_{\text{P-in,win}} < T_{\text{L}} \tag{3-2}$$

Where, T_{S} is the PCM solidus temperatures, ℃;

T_{L} is the PCM liquidus temperatures, ℃;

$T_{\text{P-out,win}}$ is the outer surface temperature of the PCM layer in winter;

$T_{\text{P-in,win}}$ is the inner surfaces of the PCM layer in winter, ℃;

$T_{\text{P-out,sum}}$ is the outer surface temperature of PCM layer in summer, ℃

$T_{\text{P-in,sum}}$ is inner surfaces temperature of the PCM layer in summer, ℃;

In addition, if the PCM phase-change temperature range can meet the demand of the full phase change in summer and winter, PCM has also the phase change effect obviously in the transition seasons.

Moreover, there are two relative constraint conditions.

(1) To maximize the phase-change latent heat per the temperature variation, the PCMs phase-change temperature range should be as small as possible under the certain phase-change latent heat of the PCM layer.

(2) Wall temperature in winter is much less than that in summer and there is the lowest temperature difference in inner surfaces under the conditions of heating in winter and air-conditioning in summer. And indoor air temperatures are 20 ℃ in winter and 25 ℃ in summer for the residential and public buildings respectively, so the corresponding relations of wall inner surface temperatures between winter and summer is following:

$$T_{\text{P-in,sum}} - T_{\text{P-in,win}} \geq T_{\text{W-in,sum}} - T_{\text{W-in,win}} > T_{\text{in,sum}} - T_{\text{in,win}} = 25°\text{C} - 20°\text{C} = 5°\text{C} \tag{3-3}$$

Where, $T_{\text{in,win}}$ is indoor air temperatures in winter, ℃;

$T_{\text{in,sum}}$ is indoor air temperatre in summer, ℃;

$T_{\text{W-in,win}}$ is the wall inner surface temperature in winter, ℃;

$T_{\text{W-in,sum}}$ is the wall inner surface temperature in summer, ℃;

Combination with Equations (3-1)~(3-3), the calculation principle of the PCM phase-change temperature range can be obtained as follows:

$$T_S < T_{\text{P-out,win}} < T_{\text{P-in,win}} < T_{\text{W-in,sum}} < T_{\text{p-out,sum}} < T_L \qquad (3\text{-}4)$$

According to Equation (3-4), outer surface temperature of the PCM layer in winter is the solidus temperature of PCM, while outer surface temperature of the PCM layer in summer is the liquidus temperature of PCM. Therefore, how to determine the outside surface temperature of the PCM layer is a key problem to calculate the PCM phase-change temperature range.

3.3 Related inference of the PCM phase change range

In general, outdoor thermal environment changes alternately all the year round, but daily outdoor thermal environment is more similar in a shorter period such as a week, a mouth and even a season. Such as in Chengdu region, outdoor air temperature are separately fluctuates 2℃~10℃ in winter, and 22℃ ~32℃ in summer. In addition, indoor air temperature can be regarded as constant, especially in air-conditioning and heating room, they are be set as 20℃ in winter and 25℃ in summer. Therefore, under the certain period, the average temperature of any wall layer can be approximately considered to be constant. Meanwhile, at the period of 24h, the transient temperature of any wall layer has a certain fluctuation due to the alternation of day and night.

So, the temperature fluctuation arrange of any wall layer can be defined as follows:

$$T_{\text{base}} - A \le T \le T_{\text{base}} + A \tag{3-5}$$

Where, $T_{\text{L-base}}$ is the average value of any layer temperature in a day, ℃;

A is the temperature fluctuation of any layer temperature in a day, ℃;

According to Equation (3-5), it can be found that any layer temperature can include the base temperature and the fluctuation temperature. For the base temperature, the stable algorithm is adopted. According to the thermoelectricity analogy method[6-7]. Figure 3-4 shows the thermoelectricity analogy circuit diagram of the multilayer wall integrating with the PCM layer.

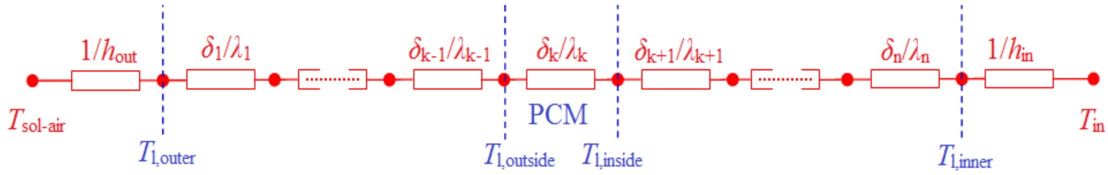


Figure 3-4 Thermoelectricity analogy circuit diagram of multilayer wall

According to the thermoelectricity analogy circuit diagram, outer surface base temperature of the PCMs layer can be obtained as following:

$$T_{\text{base, P-out}} = \frac{T_{\text{sol-air,avg}} - T_{\text{in}}}{\frac{1}{h_{\text{out}}} + \sum_{i=1}^{n}\frac{\delta_i}{\lambda_i} + \frac{1}{h_{\text{in}}}} \cdot \left(\sum_{i=k}^{n}\frac{\delta_i}{\lambda_i} + \frac{1}{h_{\text{in}}}\right) + T_{\text{in}} \tag{3-6}$$

where, λ_i is the thermal conductivity of the ith layer, W/(m·K);

δ_i denotes the thickness of the ith layer, m;

h_{in} is the inside convective heat transfer coefficient, (W/(m·K));

h_{out} is the outside convective heat transfer coefficient, (W/(m·K));

$T_{\text{sol-air,avg}}$ is the average value of outdoor comprehensive temperature, ℃;

The outer thermal environment fluctuation is the power source of temperature fluctuation in any wall layer. Outer comprehensive temperature wave, which transfer from outer surface to inner surface, must be damped due to the thermal inertia of the wall layer, surface thermal storage coefficient in the interface between two different wall materials and so on. Due to the fact that the full phase change of PCM is necessary, so the damping decrement of outdoor comprehensive temperature wave can be calculated under the consideration of the full phase change of PCM as following:

$$\frac{A_{\text{Sol-air}}}{A_{\text{W-in}}} = e^{\frac{\sum D}{\sqrt{2}}} \cdot \frac{S_n + h_{\text{in}}}{S_n + Y_n} \cdots \frac{S_k + Y_{k+1}}{S_k + Y_k} \cdots \frac{S_1 + Y_2}{S_1 + Y_1} \cdot \frac{h_{out} + Y_1}{h_{out}} \tag{3-7}$$

Where, D is wall thermal inertia;

$A_{\text{W-in}}$ is the temperature amplitude of inner surface, ℃;

$A_{\text{Sol-air}}$ is the temperature amplitude of outdoor comprehensive temperature, ℃

Y_{i} is the surface heat storage coefficient of the ith layer, W/(m^2·K);

S_{i} is the wall material heat storage coefficient of the ith layer, W/(m^2·K);

For the innermost layer, namely when i=n, Y_{n} is defined as following Y_i is defined as following:

$$Y_n = \frac{R_{\text{n}} S_n^2 + h_{\text{in}}}{1 + R_{\text{n}} h_{\text{in}}} \tag{3-8}$$

And if i<n, Y_i is defined as following:

$$Y_i = \begin{cases} S_i & D_i \geq 1 \\ \dfrac{R_i S_i^2 + Y_{i+1}}{1 + R_i Y_{i+1}} & D_i < 1 \end{cases} \tag{3-9}$$

D_i is inertia of the *i*th layer and D is the wall comprehensive and can be calculated as following:

$$D = \sum_{i=1}^{N} D_i = \sum_{i=1}^{n} R_i \cdot S_i = \sum_{i=1}^{k} \frac{\delta_i}{\lambda_i} \cdot \sqrt{\frac{2\pi\lambda_i C_{Pi}\rho_i}{z}} \tag{3-10}$$

Where, z is outdoor comprehensive temperature fluctuation period, 86400s;

ρ_{i} is the material density of the ith layer, kg/m^3;

C_{Pi} is the heat capacity of the ith layer, J/(kg·K);

Suppose the phase change can be occurred entirely, the phase-change latent heat of PCM can be equivalent to heat capacity by the following method:

$$C'_{PCM} = C_{PCM} + \frac{L_{PCM}}{T_{\text{P-out,sum}} - T_{\text{P-out,win}}} \tag{3-11}$$

Where, C_{PCM} donate the heat capacity of PCM, J/(kg·K);

L_{PCM} is the phase-change latent heat of PCM, J/kg;

When outdoor air comprehensive temperature wave arrives at the outer surface of the PCM layer, which is assumed as the kth layer, the damping decrement can be calculated owing to the outside wall of the PCM layer as following:

$$\frac{A_{sol-air}}{A_{P-out}} = \frac{S_{k-1}+Y_k}{S_{k-1}+Y_{k-1}} \cdots \frac{S_1+Y_2}{S_1+Y_1} \cdot \frac{h_{out}+Y_1}{h_{out}} e^{\frac{\sum D_{P-out}}{\sqrt{2}}} \tag{3-12}$$

Where, $D_{\text{P-out}}$ is outside wall thermal inertia of the PCM layer ;

$A_{\text{P-out}}$ is the outer surface temperature amplitude of the PCM layer, ℃;

And the outer surface temperature amplitude of the PCM layer can be obtained by Equation (3-13) as following:

$$A_{P-out} = \frac{A_{sol-air}}{\frac{S_{k-1}+Y_k}{S_{k-1}+Y_{k-1}} \cdots \frac{S_1+Y_2}{S_1+Y_1} \cdot \frac{h_{out}+Y_1}{h_{out}} e^{\frac{\sum D_{P-out}}{\sqrt{2}}}} \tag{3-13}$$

From the above, the outer surface temperature change range of the PCM layer can be obtained as following:

$$\begin{gathered}\frac{T_{\text{sol-air,avg}} - T_{\text{in}}}{\frac{1}{h_{\text{out}}} + \sum_{i=1}^{n}\frac{\delta_i}{\lambda_i} + \frac{1}{h_{\text{in}}}} \cdot \left(\sum_{i=k}^{n}\frac{\delta_i}{\lambda_i} + \frac{1}{h_{\text{in}}}\right) + T_{\text{in}} - \frac{A_{sol-air}}{\frac{S_{k-1}+Y_k}{S_{k-1}+Y_{k-1}} \cdots \frac{S_1+Y_2}{S_1+Y_1} \cdot \frac{h_{out}+Y_1}{h_{out}} e^{\frac{\sum D_{P-out}}{\sqrt{2}}}} \\ < \quad T_{P-out} \quad < \\ \frac{T_{\text{sol-air,avg}} - T_{\text{in}}}{\frac{1}{h_{\text{out}}} + \sum_{i=1}^{n}\frac{\delta_i}{\lambda_i} + \frac{1}{h_{\text{in}}}} \cdot \left(\sum_{i=k}^{n}\frac{\delta_i}{\lambda_i} + \frac{1}{h_{\text{in}}}\right) + T_{\text{in}} + \frac{A_{sol-air}}{\frac{S_{k-1}+Y_k}{S_{k-1}+Y_{k-1}} \cdots \frac{S_1+Y_2}{S_1+Y_1} \cdot \frac{h_{out}+Y_1}{h_{out}} e^{\frac{\sum D_{P-out}}{\sqrt{2}}}}\end{gathered} \tag{3-14}$$

3.4 Theory calculation method of PCMS phase change range

According to Equation (3-4), outer surface temperature of the PCM layer in winter is the PCM solidus temperature, while outer surface temperature of the PCM layer in summer is the PCM liquidus temperature. However, the outer surface of the PCM layer fluctuates with outdoor air temperature naturally. Therefore, solidus and liquidus temperatures should be considered the downward fluctuation in winter and the upward fluctuation in summer, respectively. Combining with the above analysis, solidus and liquidus temperatures can be obtained as following, respectively:

$$T_S = (T_{in})_{win} + \frac{(T_{sol\text{-}air,avg} - T_{in})_{win}\left(\sum_{i=k}^{n}\frac{\delta_i}{\lambda_i} + \frac{1}{h_{in}}\right)}{\frac{1}{h_{out}} + \sum_{i=1}^{n}\frac{\delta_i}{\lambda_i} + \frac{1}{h_{in}}} - \frac{A_{sol\text{-}air,win}}{\frac{S_{k-1}+Y_k}{S_{k-1}+Y_{k-1}}\cdots\frac{S_1+Y_2}{S_1+Y_1}\cdot\frac{h_{out}+Y_1}{h_{out}}e^{\frac{\sum_{i=1}^{k-1}D_i}{\sqrt{2}}}} \tag{3-15}$$

$$T_L = (T_{in})_{sum} + \frac{(T_{sol\text{-}air,avg} - T_{in})_{sum}\left(\sum_{i=k}^{n}\frac{\delta_i}{\lambda_i} + \frac{1}{h_{in}}\right)}{\frac{1}{h_{out}} + \sum_{i=1}^{n}\frac{\delta_i}{\lambda_i} + \frac{1}{h_{in}}} + \frac{A_{sol\text{-}air,sum}}{\frac{S_{k-1}+Y_k}{S_{k-1}+Y_{k-1}}\cdots\frac{S_1+Y_2}{S_1+Y_1}\cdot\frac{h_{out}+Y_1}{h_{out}}e^{\frac{\sum_{i=1}^{k-1}D_i}{\sqrt{2}}}} \tag{3-16}$$

Three are also three notes should be pointed about theory calculation methods of confirming PCM layer phase change:

(1) The theory calculation method is arranging PCM phase change according the whole-year condition design phase change temperature. However ,the calculation methods equation(3-15 and 3-16) is also suitable for any period and any season.

(2) When calculating PCM phase change range under whole-year condition, outdoor temperature should consider the coldest and hottest summer in typical year according theory methods (equation (3-15) and (3-16)); however, if designing PCM phase change according a certain period and season, 5%~10% coldest and hottest time should be considered during calculating outdoor temperature.

(3) The theory method is just used for confirming reasonable PCM phase change range, energy saving rate should be analyzed future; however, just when PCM phase change range is confirmed reasonably, PCM can play the phase change heat storage potential efficiently, the research on PCMs in buildings can be meaningful.

3.5 Factors influencing PCMs phase change range arrangement

According to Equation.(3-15 and 3-16) there are three main aspects affecting PCM solidus and liquidus temperatures:

(I) Indoor air temperature for the heating in winter and the air-conditioning in summer;

(II) Outdoor thermal environment (The average value and the fluctuation amplitude of outdoor comprehensive temperature in winter and summer);

(III) The location of the PCM layer;

And usually, the design indoor temperatures are 20 ℃ for heating in winter and 25 ℃ for air-conditioning in summer. In addition, outdoor thermal environment and wall parameters are considered as below. In order to analyze the influence of above factors on PCM phase-change temperature range in China, the typical wall model integrated with the PCM layer is established as shown in Figure. 3-5, where a, b and c are the thicknesses of the plaster layer, the PCM layer and the wall structure layer, and L is the distance, which the PCM layer is far away from inner plaster layer.

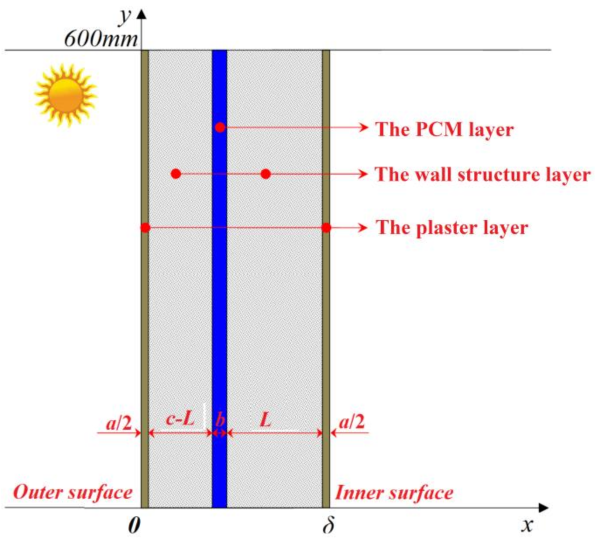


Figure 3-5 The typical model of wall integrated with the PCM layer

3.5.1 Effect rule of outdoor climate condition on PCM phase change range

In order to make qualitative analysis on the effect rule of outdoor temperature on phase change range of PCM layer, in this chapter, the wall structure and performance parameter keep constant. Table 3-2 shows the material thermal physical property of layers. The thickness of plaster layer, PCM layer and sintered brick layer are separately set as a=20mm, b=20mm and c=220mm. There are three situation for the location of PCM layer, namely it is located in the wall inner surface, middle and outer surface, L=0mm, 110mm and 220mm.

From equations (3-15) and (3-16), it can be found that the outer thermal environmental factors influencing PCM phase change range is outdoor comprehensive temperature average value and amplitude, the calculation method of outdoor comprehensive temperature is shown as follows:

$$T_{\text{sol-air}} = T_{\text{out}} + \frac{\alpha I}{h_{\text{out}}} - T_r \tag{3-17}$$

Where, h_{out} is wall outer surface convective heat transfer coefficient, (m•K); T_{out} is outdoor air temperature,°C; α wall absorption coefficient; I is solar radiation intensity, W/m2; T_r is wall effective long wave radiation temperature,°C;

Therefore, when make analysis the influence of outdoor comprehensive temperature average value, the value in winter and summer are separately -5°C~20°C and 25°C~50°C, the amplitude is 10°C; in addition, when make the influence of outdoor comprehensive temperature amplitude, the value is 5℃~15℃, the outdoor averagely temperature in summer and winter are separately 35°C and 5°C.

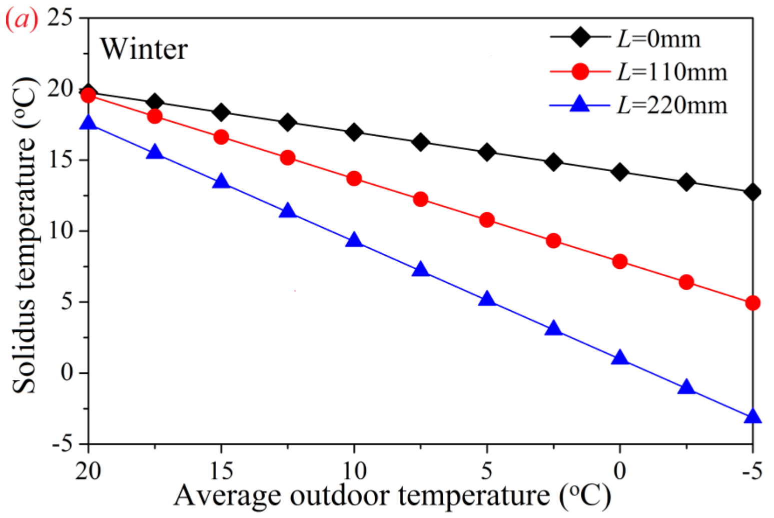
Table 3-2 Material thermal physical property of layers

Materials	Density (kg/m^3)	Heat capacity (J/(kg K))	Heat conductivity coefficient (W/(m K))	Phase change latent heat (J/kg)
Plaster layer	1860	840	0.87	-
Sintered brick layer	1700	1051.6	0.63	-
PCM layer	1300	1785	0.45(liquid), 0.7(solid)	178500

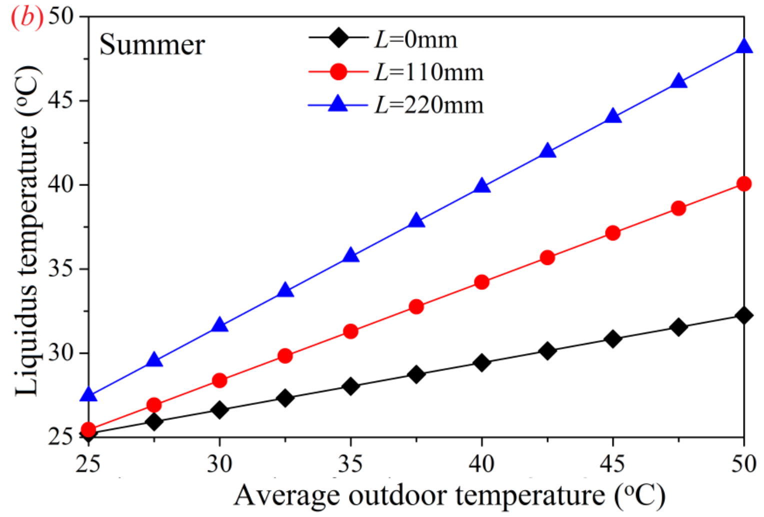
Figure.3-6. shows when outdoor temperature fluctuation amplitude is 10 ^{o}C, PCM layer (a)solidus temperature and (b)liquidus temperature separately variation with average outdoor temperature. It can be found that, for a certain wall, average outdoor temperature determine the liquidus temperature in summer. With the increasing of summer average outdoor temperature, liquidus temperature of PCM layer increases linearly. On the other hand, the result is opposite for solidus temperature in winter as shown in Figure.3-6(a). With the decrease of average outdoor

temperature, the solidus temperature decreases linearly. Above research shows that in hotter climate region, PCM layer has a higher phase change range, and a lower one in colder climate region.

In addition, through the results comparison when PCM layer locations are L=0mm，110mm and 220mm, it can be founded that the nearer PCM layer to wall inner surface, the lower liquidus temperature，higher solidus temperature and smaller phase change slope. Main reasons are PCM layer outer wall has a more obviously resistance effect with its shouting distance to wall inner surface.



(a) Relationship between average outdoor temperature and solidus temperature



(b) Relationship between average outdoor temperature and liquidus temperature

Figure 3-6 Variation of PCM layer (a)Solidus temperature and (b) liquidus temperature with average outdoor temperature

Figure.3-7. shows when outdoor temperature is 35°C in summer and 5°C in winter, PCM layer (a)solidus temperature and liquidus temperature separately variation with average outdoor temperature amplitude. It can be found that, with the increasing of outdoor temperature amplitude, liquids temperature of PCM layer increases and solidus temperature decrease which means a bigger phase change range.

In addition, from the comparison results of PCM layer locations when L=0mm，110mm and 220mm, it can be founded that the nearer PCM layer to wall inner surface, the smaller solidus temperature and liqudus temperature slope. Main reasons are PCM layer outer wall thermal inertia has a more obviously attenuation effect to outdoor temperature fluctuation with its small distance to wall inner surface.

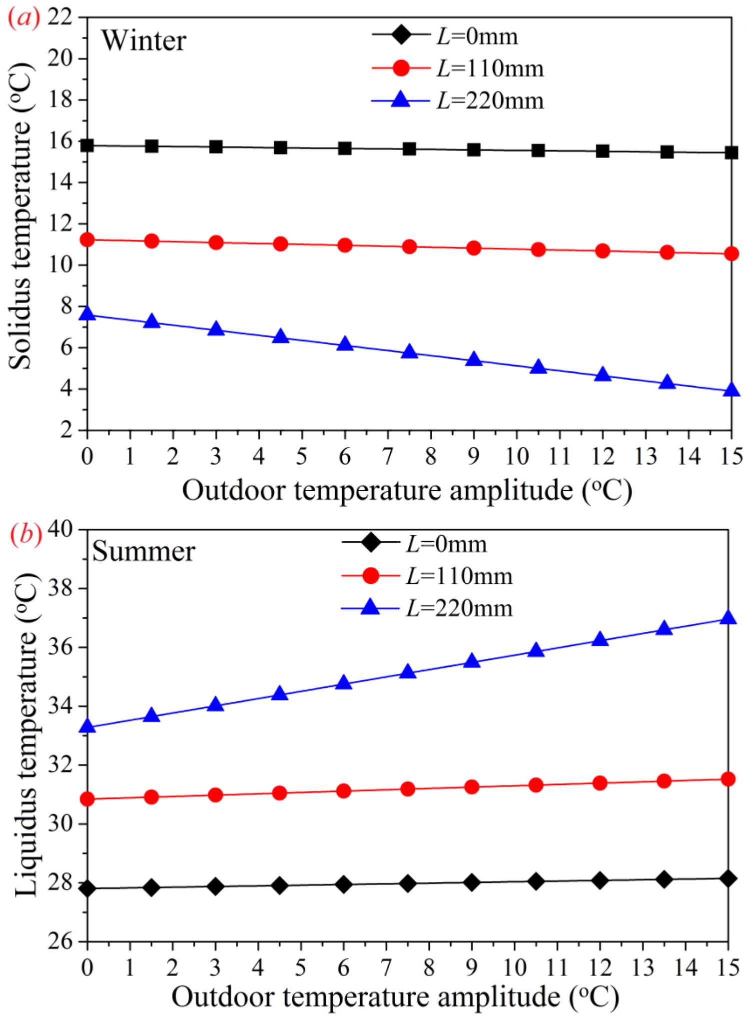


Figure 3-7 Variation of PCM layer (a)Solidus temperature and (b) liquidus temperature with outdoor temperature fluctuation

3.5.2 Effect rule of wall structure on PCM phase change range

In order to make qualitative research on influence rule of wall structure on PCM Phase Change Range, average outdoor temperature in summer and winter are set up separately as 35 °C and 5 °C, temperature fluctuation are set up as 10 °C. Figure 3-8. shows variation of PCM phase change temperature with PCM Layer position. With the moving of PCM from wall inner surface to outer surface (namely increase of L), solidus temperature is decreasing and liquidus temperature is improving, therefore the whole phase change range is decreasing. The reason is the difference of outdoor temperature between summer and winter is higher than that of temperature difference of indoor temperature. Therefore, the closer to wall inner surface, the smaller wall layer temperature difference of summer and winter which leading to the increasing linearly of PCM phase change range.

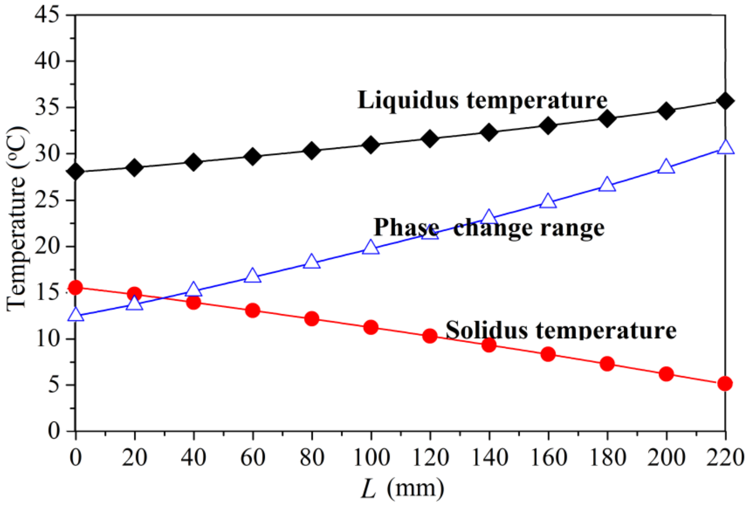


Figure 3-8 Variation of PCM Phase change temperature with PCM Layer position

Except the location of PCM layer, the thickness of wall sintered brick is also a factor of the wall structure. Figure.3-9. shows when PCM is located in the inner of wall sintered brick layer, namely L=0mm, the variation of PCM layer phase change with wall thickness of sintered brick layer. With the increase of thickness of wall sintered brick layer, solidus temperature is increasing and liquidus temperature is decreasing. The reason of this phenomenon is the thicker the sintered brick layer located in the outer of PCM layer, the closer of PCM layer to wall inner surface temperature. Therefore, the PCM layer phase change range is decreasing gradually. Otherwise, conclusion also can be got when PCM layer is located in the outer of sintered brick layer, the result is opposite.

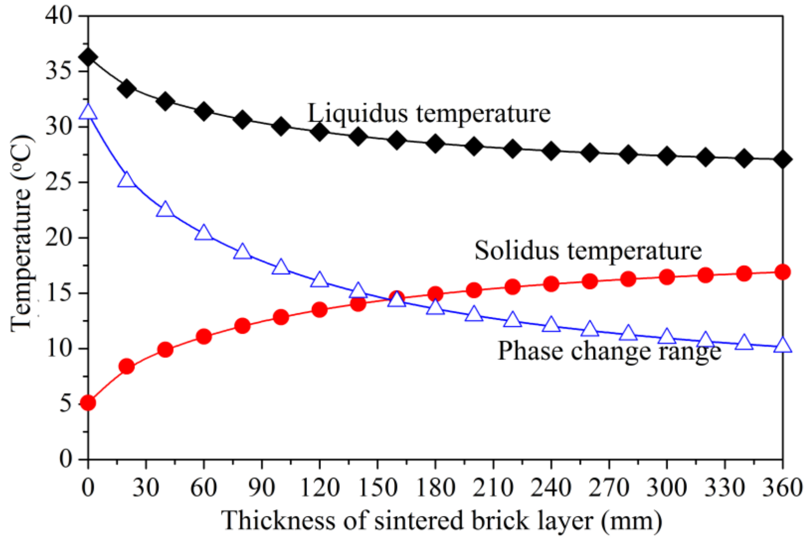


Figure 3-9 Variation of PCM Phase change temperature with thickness of sintered brick layer

Figure 3-10 shows when PCM is located in the inner of wall sintered brick layer and the thickness of sintered brick layer is 220mm, variation of PCM phase change temperature with heat conductivity coefficient of sintered brick layer. With the increasing of heat conductivity coefficient of wall sintered brick layer, solidus temperature is increasing and liquidus temperature is decreasing, so that PCM phase change range is increasing. The reason is that with the increasing of wall sintered brick layer heat conductivity coefficient, the poorer the PCM layer outer wall heat insulation property, and the temperature fluctuation of PCM layer is closer to the variation of outdoor temperature, so the bigger the PCM phase change range is.

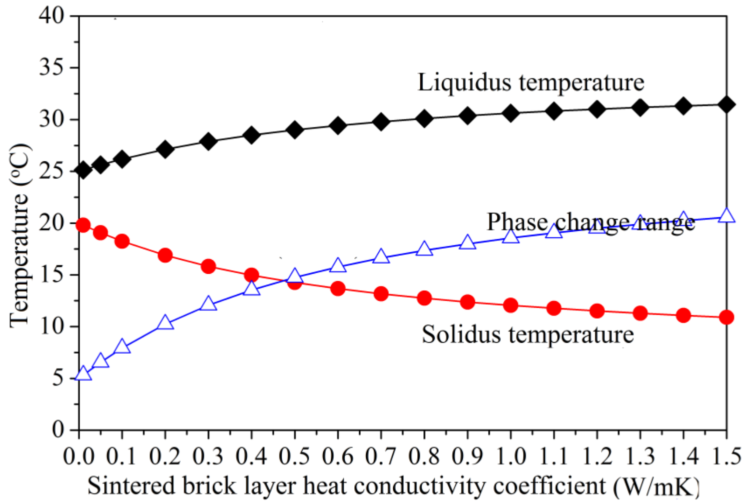


Figure.3.10 Variation of PCM Phase change temperature with heat conductivity coefficient of sintered brick layer

3.6 Summary

Owing to the fact that the PCM layer phase-change temperature range is a important factor affecting the phase-change degree of PCM integrated into building walls and that there is no any method to determine the PCM phase-change temperature range according to climate conditions, wall structures and so on in the previous study, our study proposes the determination methods on the PCM phase-change temperature arrange based on the traditional wall heat transfer theories.

In addition, the factors influencing PCM layer phase change range have been qualitative analyzed. Result are shown as bellows:

(1) With the increasing of summer outdoor temperature, liquids temperature of PCM layer increases linearly. The nearer PCM layer to wall inner surface, the lower liquidus temperature , higher solidus temperature and smaller phase change slope.

(3) With the increasing of outdoor temperature fluctuation, liquids temperature of PCM layer increases and solidus temperature decrease.

(4) With the moving of PCM from wall inner surface to outer surface (namely increase of L), the whole phase change range is decreasing.

(5) With the increase of thickness of wall sintered brick layer, solidus temperature is increasing and liquidus temperature is decreasing.

(6) With the increasing of heat conductivity coefficient of wall sintered brick layer, the PCM phase change range is increasing.

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Chapter Four: Verification on calculation method of PCM phase change range

4.1 Introduction

Phase change heat transfer problem is different from other heat transfer problem, its character is there is a solid-liquid face which varies with the time during solving period. Phase change latent heat is absorbed or released in this face. Except some special situation can be solved by analyzing method, most must be solved by numerical method. Several numerical models have been developed to solve phase change problems and the most commonly used are the enthalphy method, the effective heat capacity method, and the heat source method[1].

(1) Enthalpy method

Enthalpy method is developed by Eyres et al[2]. It is used for solving heat transfer problems of the temperature variations of the media's thermal properties. The latent and specific heat are combined into an enthalpy term in the enthalpy method. The numerical model is described as follows:

$$\rho \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) \tag{4-1}$$

Where, ρ is density, kg/m3;

h is enthalpy, kJ/kg;

t is time, seconds;

x is space distance, m;

λ is heat conductivity, W/m ℃;

T is temperature, ℃;

The enthalpy at a node is calculated depend on the temperature. The temperature-enthalpy function is shown as follows:

$$T = \begin{cases} \dfrac{h}{c_s}, & h \le c_s \times (T_m - \in) \\ \dfrac{h + \left(\dfrac{c_l - c_s}{2} + \dfrac{L}{2\times\in}\right)\times(T_m - \in)}{\left(\dfrac{c_l - c_s}{2} + \dfrac{L}{2\times\in}\right)}, & c_l \times (T_m - \in) < h \le c_s \times (T_m - \in) + L \\ \dfrac{h - (c_s - c_l)\times T_m - L}{c_l}, & h \ge c_l \times (T_m - \in) + L \end{cases} \tag{4-2}$$

Where, T is temperature, ℃;

c_s is specific heat of the solid phase, kJ/kg ℃;

c_l is specific heat of the liquid phase, kJ/kg ℃;

L is latent heat of fusion, kJ/kg ;

ϵ is half range of melting temperatures, ℃ (K);

T_m is melting temperature, ℃ ;

(2) Effective heat capacity method

Hashemi and Sliepcevich developed the effective heat capacity method to solve the one-dimensional heat conduction equation during phase change transitions[3]. In this method, the effect of enthalpy is replaced by the heat capacity term by using various heat capacities. The equation of the effective heat capacity method is shown below.

$$\rho \times c_{eff} \times \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}(\lambda \frac{\partial T}{\partial x}) \tag{4-3}$$

Where, c_{eff} is the effective heat capacity, kJ/kg ℃.

In addition, two method are used for estimating the effective heat capacity: a numerical approximation and an analytical/empirical relationship. If the properties of the PCMs are provided on a limited basis, the analytical/ empirical relationships can be used. For example, if DSC data are not available, but limited manufacturer’s or published data are available. The effective heat capacity of PCM can be confirmed by using the given PCM properties, as shown below which is proved by Voller[4].

$$c_{eff} = \begin{cases} c_s, & T \le T_m - \in (solid \quad state) \\ \frac{c_s + c_l}{2} + \frac{L}{2\in}, & Tm - \in < T < Tm + \in (pha\text{se} \quad transition \quad state) \\ c_l, & T > T_m + \in (liquid \quad state) \end{cases} \tag{4-4}$$

Where, ∈ is melting temperature range, ℃.

When the detailed properties of the PCMs is available, the numerical approximation can be used for calculating the effective heat capacity. The calculation equation is shown as below[5]:

$$c_{eff} = \frac{\Delta h}{\Delta T} = \frac{h^n - h^{n-1}}{T^n - T^{n-1}} \tag{4-5}$$

Where, n is new time step, seconds; n-1 is previous time step, seconds.

(3) Heat source method

Eyres developed the heat source method in which enthalpy of PCM is divided into two parts: the specific heat and the latent heat[2]. Among what, the latent heat is seen as a heat sore term as shown in equation (4-6):

$$\rho \times c_{avg} \times \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda \frac{\partial T}{\partial x}) - \rho \times L \times \frac{\partial f_l}{\partial t} \tag{4-6}$$

Where, c_{avg} is average specific heat of the solid and liquid phases, kJ/kg ℃;

L is latent heat of fusion, kJ/kg;

f_l is liquid fraction.

The liquid fraction is decided by equation (4-7)[6]:

$$f_l = \begin{cases} 0, & T \le T_m - \in (solid \quad state) \\ \dfrac{(T - T_S)}{(T_l - T_S)} & T_m - \in < T < T_m + \in (solid\, transition \quad state) \\ 1, & T > T_m + \in (liquid \quad state) \end{cases} \tag{4-7}$$

Where, Ts is the lowest temperature in the melting temperature range, ℃;

T_l is the highest temperature in the melting temperature range, ℃;

In this chapter, the dynamic heat transfer model (namely enthalpy value and porous media) of the multilayer walls integrated with the PCM layer is established and verified by the experimental data and the published data. And then this model is used to verify if the theoretic algorithm of Equation. (3-15) and (3-16) can predict the PCM phase-change temperature range efficiently and accurately, the verification is carried on under the different PCM phase-change occurrence design period, the different locations of the PCM layer and the different wall structures.

4.2 Heat transfer model of multi-layer wall with PCMs layer and numerical simulation description

4.2.1 Heat transfer model of multi-layer wall with PCMs layer

Actually, the wall heat transfer is three-dimensional, but as the wall heat transfer occurs between inner and outer surfaces and thereby, there is only heat transfer along the wall thickness. Therefore, a three-dimensional problem can be approximately simplified to one-dimensional heat transfer along the wall thickness directions. The typical wall model is same with that showed in Figure 3-5. The thickness of plaster layer, PCM layer and sintered brick layer are separately a=20mm, b=20mm and c is 220mm. The material thermal physical property of layers are shown in Table 3-1. In addition, Figure 4-1 shows a composite wall of N-layers showing boundary conditions and grid arrangement. Meanwhile, convection thermal boundary conditions are present on the both sides of wall. At the wall outer surface, sol-air temperature includes the effect of outdoor air temperature combined with solar radiation. Air temperature at the wall inner surface represents indoor air temperature, which may be equal to the set temperature of air-conditioning.

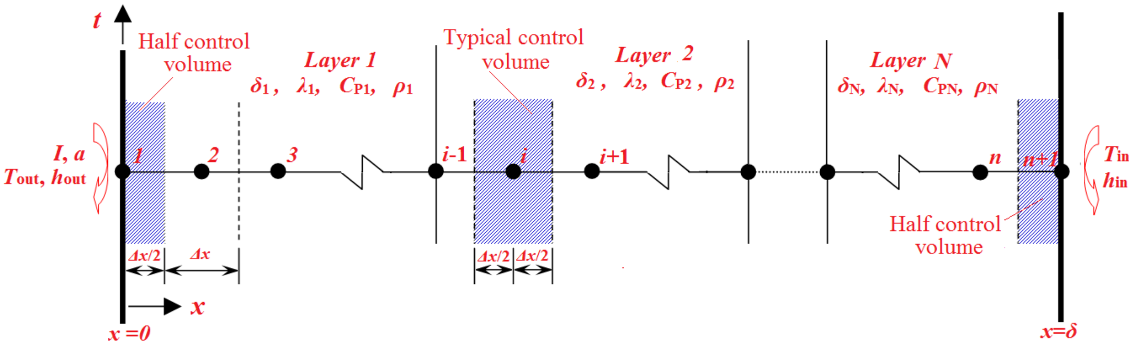


Figure 4-1 Composite wall of N-layers showing boundary conditions and grid arrangement.

Under the outer thermal environment variation with time, the heat transfer of the multilayer wall integrated with the PCM layer is the transient heat conduction with both melting and solidification of PCM. If a one-dimensional coordinate system is established with the coordinate origin at the thickness direction x, an enthalpy-porosity model is utilized to simulate such dynamic heat transfer process[7], and the governing equation is described as the following equation:

$$\rho_i \frac{\partial h_i}{\partial t} = \frac{\partial}{\partial x}(\lambda_i \frac{\partial T_i}{\partial x}) \qquad (4\text{-}8)$$

Where, ρ is the material density, kg/m3;

h is the material enthalpy value;

λ is the thermal conductivity, W/(m·K);

T denotes the material temperature, ℃;

t is time, s;

In the non-PCM layer, h can be shown as following:

$$h = c \times T \tag{4-9}$$

Where, *c* expresses specific heat, J/(kg·K);

In the PCM layer, h can be shown as following:

$$h = \begin{cases} \int_{T_0}^{T} c_{ps} \partial T, & T < T_s \\ \int_{T_0}^{T_s} c_{p,s} \partial T + \int_{T_S}^{T} c_{p,\mathrm{m}} \partial T, & T_s < T < T_L \\ \int_{T_0}^{T_s} c_{p,s} \partial T + \int_{T_S}^{T_L} c_{p,\mathrm{m}} \partial T + \int_{T_L}^{T} c_{p,L} \partial T, & T_L < T_L \end{cases} \tag{4-10}$$

Where, T_0 is the temperature point when *h* is equal to zero, ℃;

T_s and T_L are solidus and liquidus temperatures respectively, ℃;

$c_{p,s}$ and $c_{p,l}$ are the constant specific heat capacities in the solid and liquid states, respectively, J/(kg·K);

$c_{p,m}$ is the equivalent specific heat capacity for the phase transition process and is assumed to be uniform, J/(kg·K).

The convective heat transfer boundary conditions are adopted on the outer and inner surfaces(x = 0 and δ) and can be expressed as following:

On the outer surface (*x=0*)

$$-\lambda \left. \frac{\partial T}{\partial x} \right|_{x=0} = h_{\mathrm{out}} (T_{\mathrm{out}} - T_{\mathrm{l,out}}) + \alpha I \tag{4-11}$$

On the inner surface (*x=δ*)

$$-\lambda \left. \frac{\partial T}{\partial x} \right|_{x=\delta} = h_{\mathrm{in}} (T_{\mathrm{l,in}} - T_{\mathrm{in}}) \tag{4-12}$$

Where, h_{in} and h_{out} are inside and outside convective heat transfer coefficients, their values are 8.7W/(m^2·K), 21W/(m^2·K);

T_{out} and T_{in} are outdoor and indoor air temperature, ℃;

$T_{\mathrm{l,out}}$ and $T_{\mathrm{l,in}}$ are outer and inner surface temperatures ℃;

α is absorption coefficient, W/m^2

4.2.2 Numerical algorithm description

The equations of the heat transfer model have been solved using the finite volume method in this simulation region. The finite volume formulation utilized in this algorithm ensures the energy conservation of wall heat transfer. A fully implicit scheme is applied for discretizing the time derivatives and a second-order central difference scheme is used for the diffusion terms. The corresponding algebraic equations are solved by the tri-diagonal matrix algorithm(TDMA). The convergence of the computations is declared at each time instant, when the following criterion is satisfied:

$$\frac{\sum_i \left| T_i^{\,n+1} - T_i^{\,n} \right|}{\sum_i \left| T_i^{\,n+1} \right|} \le 10^{-5} \tag{4-13}$$

4.3 Verification of heat transfer model

4.3.1 Literature verification

In order to verify both accuracy and reliability of the unsteady calculation procedure on the enthalpy-porosity model, the research is done to numerically simulate the dynamic thermal response of the multilayer wall integrated with the PCM layer, which is researched experimentally by Kuznik and Virgone [7] and numerically by Zhang et al[8]. Figure 4-2 shows air temperature fluctuations and compares the present results with published results. As shown in Figure 4-2, the present results agree well with the published results, especially with the simulation results of Zhang et al. [8], which demonstrates that the heat transfer model is effective and accurate, and also indicates that the predicted conclusions are verified by means of this mathematical model.

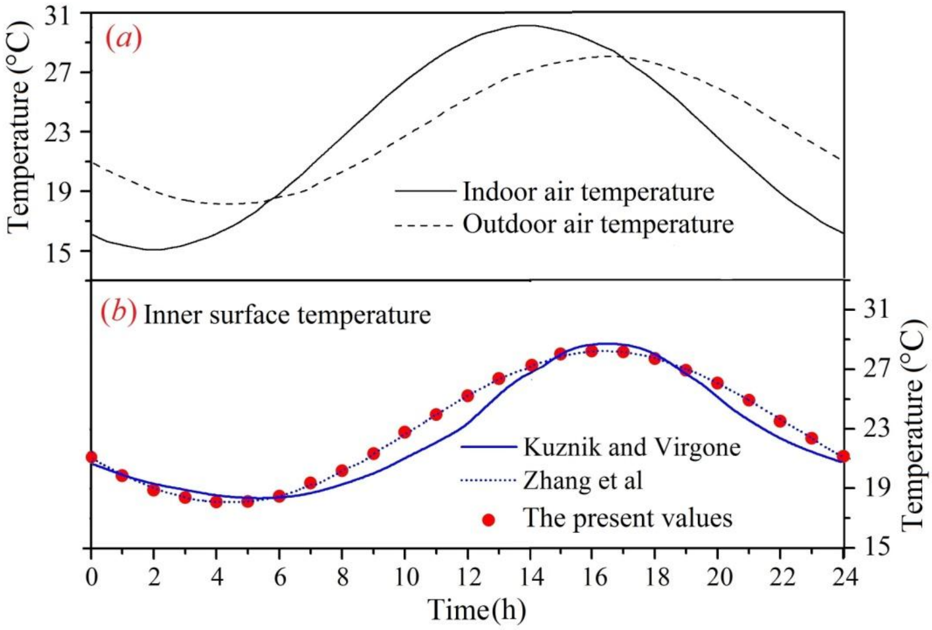


Figure 4-2 (a) Variation of indoor and outdoor air temperature and (b) comparison of the present values with the experiment values and other numerical values

4.3.2 Experimental verification

1) Experiment system

In order to explore the both accuracy and reliability of the unsteady calculation procedure on the enthalpy-porosity model. Three kinds of walls are considered as shown in Figure 4-3, walls 1-3 are walls integrated with the PCM layers in different locations. Table 4-1 shows the thermophysical properties of all materials in Walls 1-3. Table 4-2 displays the wall structure and heat transfer coefficient for four kinds of walls.

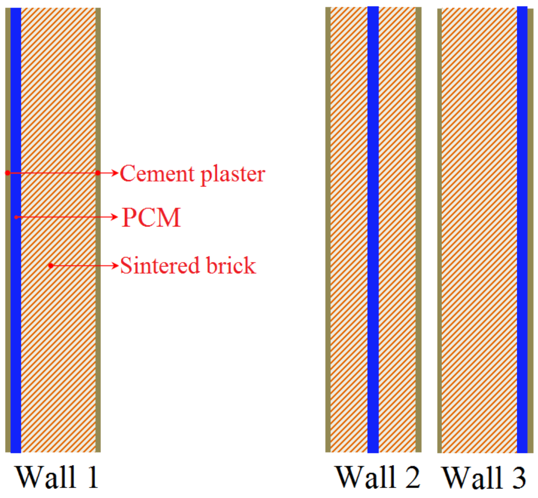


Figure 4-3 Section of the wall integrated with the PCM layer

Table 4-1 Thermophysical properties of wall materials

Wall materials	Density (kg/m^3)	Heat capacity (J/(kg K))	Thermal conductivity (W/(m K))	Phase change temperature (℃)	Latent heat (kJ/kg)
Cement plaster	1406	1050	0.3505	—	—
Sintered brick	1536	523	0.7507	—	—
PCM	1785	1300	0.523	20~29	175

Table 4- 2 Wall structure for four kinds of walls

Wall cases	Thickness and material of each layer from outside to inside
Wall 1	15mm Cement plaster + 20mm PCM + 200mm Sintered brick+15mm Cement plaster
Wall 2	15mm Cement plaster + 20mm PCM +30mm Foamed concrete + 100mm Sintered brick +15mm Cement plaster
Wall 3	15mm Cement plaster + 20mm PCM + 30mm Foamed concrete + 15mm Cement plaster

2) Experiment system

Figure 4-4 shows the experiment system, where an air conditioning is used to change indoor temperature environment and four air ducts with fans are used to ensure the indoor air temperature uniformity. Meanwhile, to obtain the same outdoor thermal environment, three kinds of walls are integrated in a base wall by a 800mm*800mm wall unit. Figure 4-5 is the experiment picture and the PCMs in the down right position is set in different place of the walls.

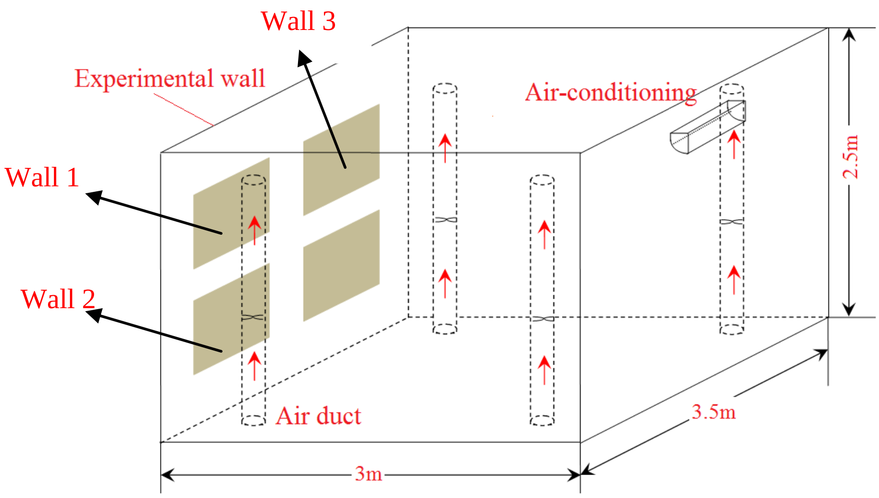


Figure 4-4 The schematic diagram of the experiment system

Figure 4-5 The schematic diagram of the experiment system

Figure 4-6 shows the arrangement diagram of thermocouples and heat flow meters. As shown in the Figure, thermocouples marked Tout and Tin are used to measure outdoor and indoor air temperature, which ones marked $T_W$out and Tw in are used to measure outer and inner surface temperature. And a heat flow meter is employed to measure inner surface heat flow. And thermocouples with errors lower than 0.30 ℃ and heat flow meters with relative error lower than 3% are selected, and all measurement data are recorded by a JTRG-II building thermal temperature automatic tester with a data-collection interval of 20 min. Figure 4-7 is the experiment equipments. Table 4-3 is the equipment parameters.

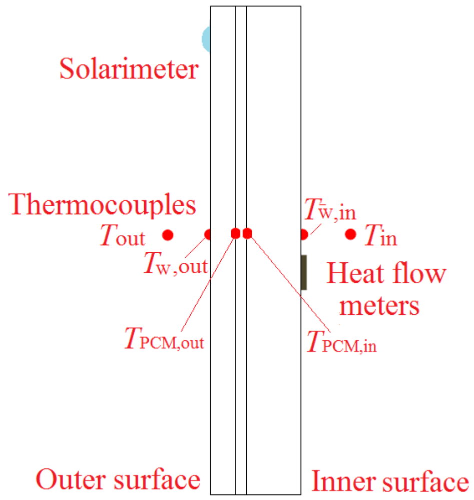


Figure 4-6 The arrangement diagram of thermocouples and heat flow meters

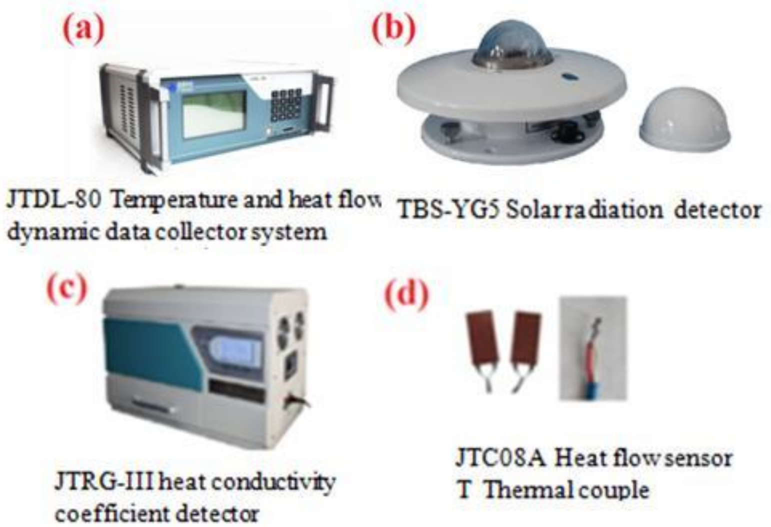


Figure 4-7 The arrangement diagram of thermocouples and heat flow meters

Table 4-3 Experiment equipments parameters

Name	Type	Measurement range	accuracy
Temperature and heat flow dynamic data collector system	JTDL-80	-20 ℃ -100 ℃ 0-2000W/m^2	±0.5 ℃ ±5%
Solar radiation detector	TBS-YG5	0-2000W/m^2	±5%
Heat conductivity coefficient detector	JTRG-III	0.02-0.8 W/(m ·K)	Tempeature: ±0.2 ℃ Heat flux uncertainty : < ±3%
Heat flux sensor	JTC08A	0-5000W/m^2	≤5%
Thermocouple	T type	-200~350 ℃	0.5 ℃

3) Climate data

The experiments were undertaken at Sichuan University (Chengdu, China) in 26th Aug, 2015. Figure 4-8 shows the variation of outdoor and indoor air temperature with time during the experiment periods. It can be clearly seen that the maximum temperature difference of outdoor air was more than 10 ℃ in a day and the indoor air temperature can be cooled to the setting one 15–20 min later after the air-conditioning operation and there is some fluctuation of indoor air temperature owing to outlet temperature fluctuation of the air-conditioning and outdoor air infiltration.

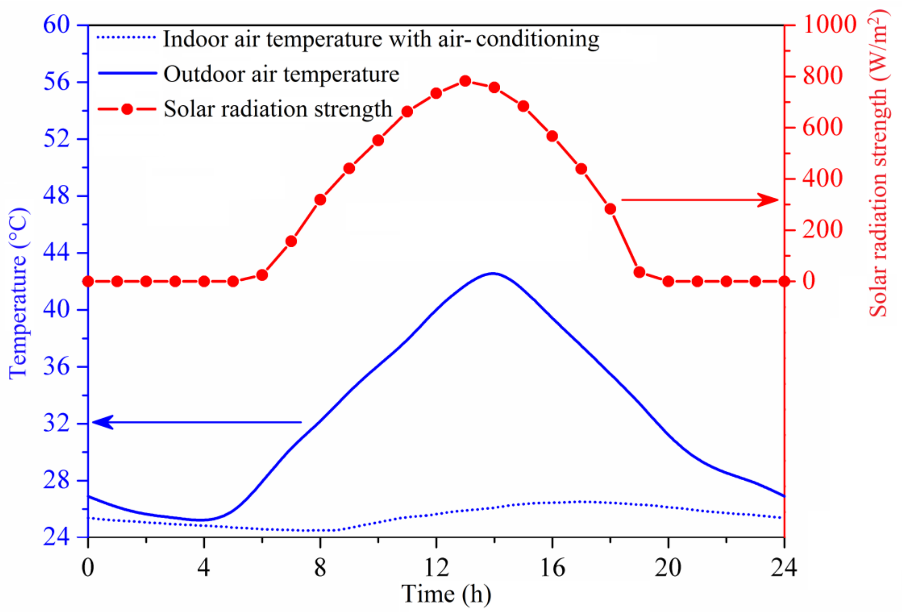
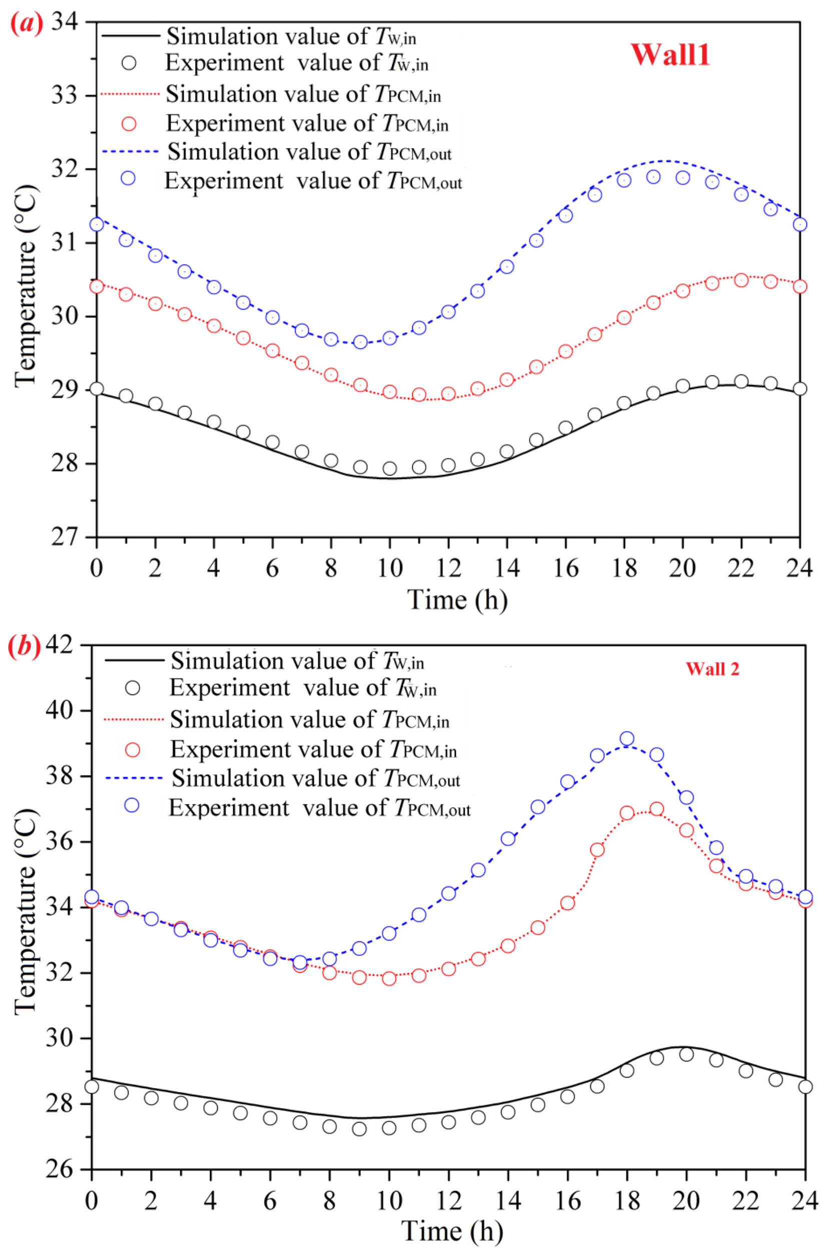
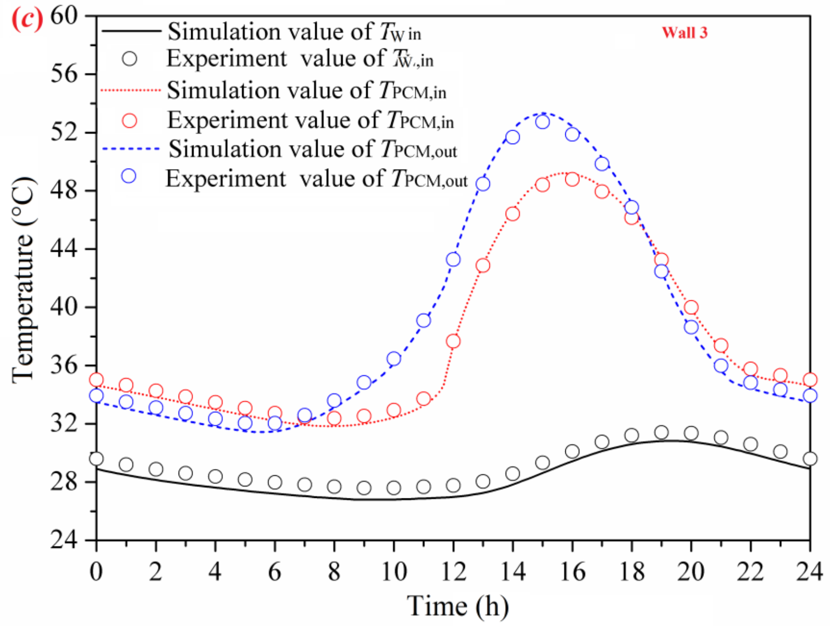


Figure 4-8 Variation of outdoor and indoor air temperature and solar radiation strength with time during the experimental period (Aug 26th)

4) Result and analysis

The verification is made from two aspects: the temperature on wall inner surface temperature and PCM layer inner surface temperature of the experimental wall and comparative object(as shown in Figure 4-9); Figure 4-9 shows the comparison between the experiment and simulation values of wall inner surface and PCM layer outer and inner surface temperature for (a) Wall 1, (c) Wall 2 and (c) Wall 3. It can be found that the simulation value is highly similar with the experimental value. And the variation trend of these two value is same for different location of PCM layer in walls. Which verified the accuracy of wall heat transfer model.

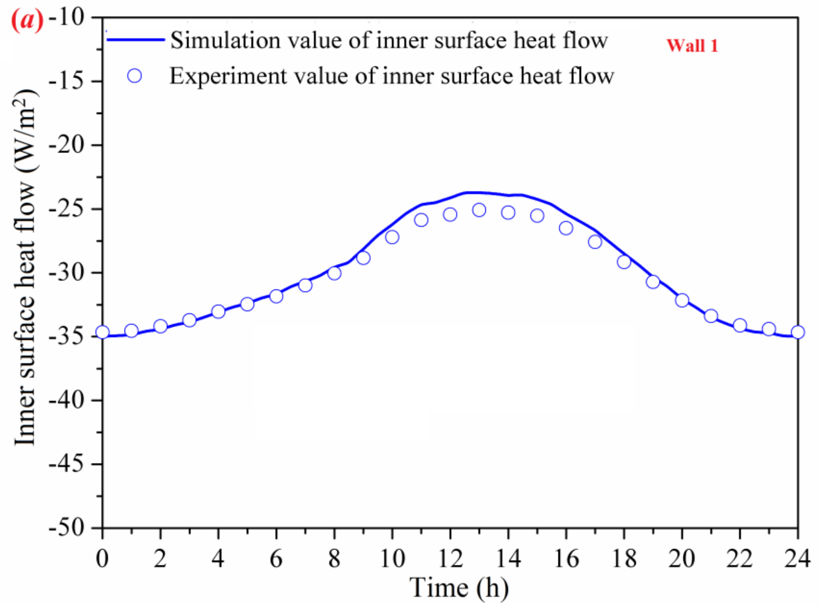




(a) Wall 3

Figure 4-9 Comparison between the experiment and simulation values of $T_{w,in}$, $T_{PCM,in}$ and $T_{PCM, out}$ for (a) Wall 1, (c) Wall 2 and (c) Wall 3

Figure 4-10 shows the Comparison between the experiment and simulation values of inner surface heat flow for three walls. The simulation value of wall inner surface heat flow highly agree with the experimental which demonstrates that the heat transfer model is effective and accurate, the analysis on energy saving of wall integrated with PCM layer is acceptable later and also indicates that the predicted conclusions are verified by means of this mathematical model.



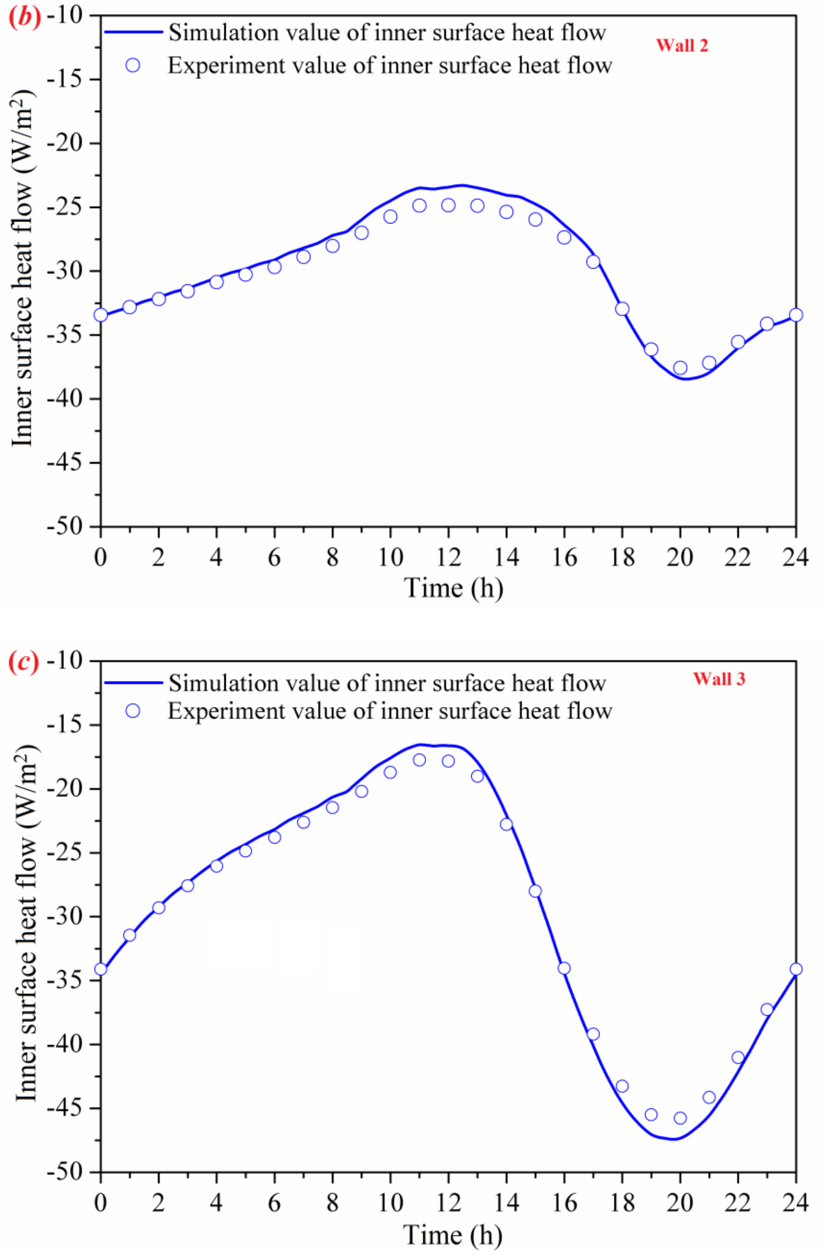


Figure 4-10 Comparison between the experiment and simulation values of inner surface heat flow for (a) Wall 1, (c) Wall 2 and (c) Wall 3

4.4 The selection of PCM phase-change range and verification of calculation method

In order to make research on accuracy of PCM phase change range obtained from theory calculation methods (equation (3-15) and (3-16)). The verification under the different outdoor thermal environment condition, location and different structure of the PCM layer has been carried out.

4.4.1 Outdoor and indoor boundary condition

When the verification on accuracy of PCM phase change range obtained from theory calculation methods (equation (3-15) and (3-16)) is done, three PCM phase-change occurrence design period are considered, including summer season (6.1~9.15), transition seasons(3.15~5.31), and all year(1.1~12.31) under the Chengdu climate conditions. Figure 4-11 displays outdoor air temperature and the horizontal total radiation of Chengdu city in a typical year.

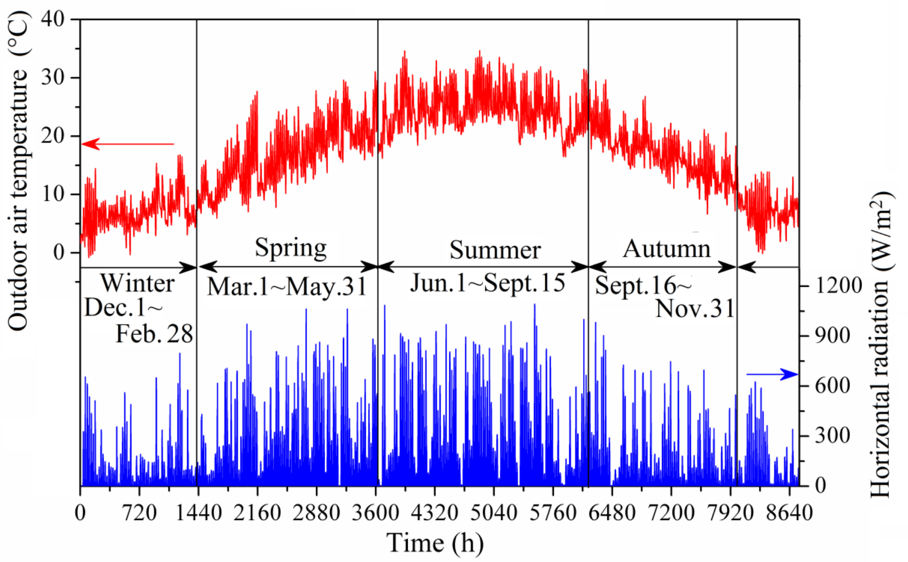


Figure 4-11 Outdoor air temperature and the horizontal total radiation of Chengdu city in a typical year

Table 4-4 gives the average value and amplitude of both the hottest and the coolest parts outdoor air temperature under the different phase-change occurrence design periods (the hottest and the coolest parts account for 10% of the phase-change occurrence period).

Table 4-4 The average value and amplitude of both the hottest and the coolest parts outdoor air temperature under the different periods of phase-change occurrence

Cases	Time period	The hottest part		The coolest part	
		Average	Amplitude	Average	Amplitude
1	Summer (Jun. 1 ~ Sept. 15)	25.81	5.13	19.28	4.20
2	Transition seasons (Mar. 1~ May. 31 & Sept. 16 ~Nov. 31)	21.87	6.05	15.14	6.04
4	All year (Jan. 1 ~ Dec. 31)	25.81	5.13	5.09	6.12

while air temperature employs the regression equation of indoor comfortable temperature proposed by Humphreys and Nicol[9-10], as following:

$$T_{in} = 0.54T_{out} + 13.5 \tag{4-14}$$

Considering the actual conditions of air-conditioning and heating, if the indoor air temperature from Equation. (4-14) is greater than 25℃ in summer, indoor air temperature is set as 25℃. Meanwhile, if the indoor air temperature from Equation. (4-14) is less than 20℃ in winter, indoor air temperature is set as 20℃. According to these, Figure 4-12 shows the variation of indoor air temperature in a typical year.

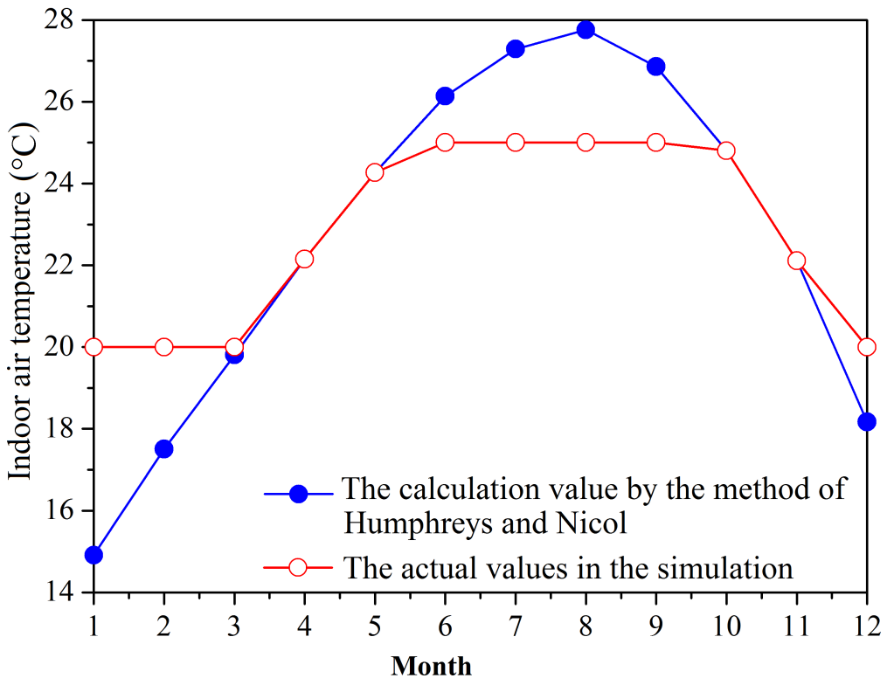


Figure 4-12 Indoor air temperature in a typical year

Although the above outdoor climate parameters belong to Chengdu city in all the year, the different PCM phase-change occurrence period must refer to the different outdoor climate parameters, which are needed in (equation (3-15) and (3-16). Meanwhile, through the comparison of the different PCM phase-change occurrence period under the same climate parameters, the accuracy of (equation (3-15) and (3-16) can be revealed deeply and the PCM phase-change difference can also be researched under the different PCM phase-change occurrence periods.

The theory algorithm of Equation. (3-15) and (3-16) are proposed to insure the PCM phase-change occurrence in 90%~95% of the design time period, so the relative relationship between the surface temperature of the PCM layer and the PCM phase-change range is the key problem to check out the effectiveness and accuracy of Equation (3-15) and (3-16). In order to quantitatively analyze the covering degree of the PCM phase-change range for surface temperature of the PCM layer, the covering rate is proposed , which is defined as following: during phase change design period, the covering rate is the ratio of the total time of PCM layer temperature in phase change range and phase change design circle, namely:

$$\eta = \frac{\sum t(T_S \le T \le T_L)}{P} \times 100\% \tag{4-15}$$

Where, P is the design time period of PCM phase-change occurrence, h;

t ($T_L \geq T \geq T_S$) is the time when the surface temperature of the PCM layer is between liquidus and solidus temperatures.

4.4.2 The selection of PCM phase-change range and verification of calculation method under the different phase-change occurrence design periods

When the verification research of calculation method of the PCM layer phase change range is done under the different outdoor thermal environment conditions, three PCM phase-change occurrence period are considered, including summer, transition seasons and all year under the Chengdu climate conditions in a typical year as shown in Figure 4-11. The wall model in this section also shown in Figure 3-5. The wall materials thermal performance property is same with what shows in Table 3-2. The thicknesses of the plaster layer, the PCM layer and the sintered brick layer are separately 20mm, 20mm and 220mm, while the PCM layer is just located in wall inner side. According to above conditions, the outdoor climate condition shown in Figure 4-11 and the theory calculation method (equation (3-15) and (3-16), Table 4-5 shows the theoretical values of PCM phase-change range under the different design periods of phase-change occurrence.

Table 4-5 Theoretical values of PCM phase-change range under the different design periods of phase-change occurrence

Time period	PCM phase-change range	
	T_S(^oC)	T_L(^oC)
Summer	23.50	27.21
Transition seasons	19.00	25.13
All year	15.94	27.40

Figure 4-13 shows variation of the surfaces temperatures (inner and outer) of the PCM layer under the different phase-change occurrence design periods. As shown in Figure 4-13, in the different phase-change occurrence design periods, inner and outer surface temperatures of the PCM layer vary between liquidus and solidus temperatures basically, which the phase-change always occur in the phase-change occurrence period and thereby that PCM has the good effects of the phase-change heat storage. Through the data processing, the covering rates of inner and outer surface temperatures are 99.4% and 96.7% for the phase-change occurrence period of summer, 91.5% and 90.7% for the phase-change occurrence period of transition seasons, and 99.6% and 96.1% for the phase-change occurrence period of all year. It shows the covering rates are greater than 95% in above four cases except the transition seasons. Table 4-6 shows the covering rate of the inner surface and outer surface temperature in different PCM phase change occurrence period, which declares theory calculation methods can make sure phase change can occur very well during phase change period.

On the other hand, during any phase-change occurrence period, there is very little time that the surface temperature of the PCM layer is beyond the PCM phase-change occurrence design period as shown during July 21th ~24th, and August 14 th ~16th in Figure 4-11 (a) and (c). This phenomenon may be resulted from higher outdoor temperature and horizontal total radiation. Time of inner and outer surface temperature of PCM layer which is higher than liqudus temperature and lower than solidus temperature is smaller than phase change design period. So the extreme climate of the typical season can be ignored due to the very short occurrence time of the extreme climate. Conversely, if the PCM phase-change range is extended to applicable for the extreme climate, it would increase drastically which is weighted against the PCM heat storage effect in the whole phase-change occurrence period. It shows the rationality of Equations. (3-15) and (3-16) on the another level.

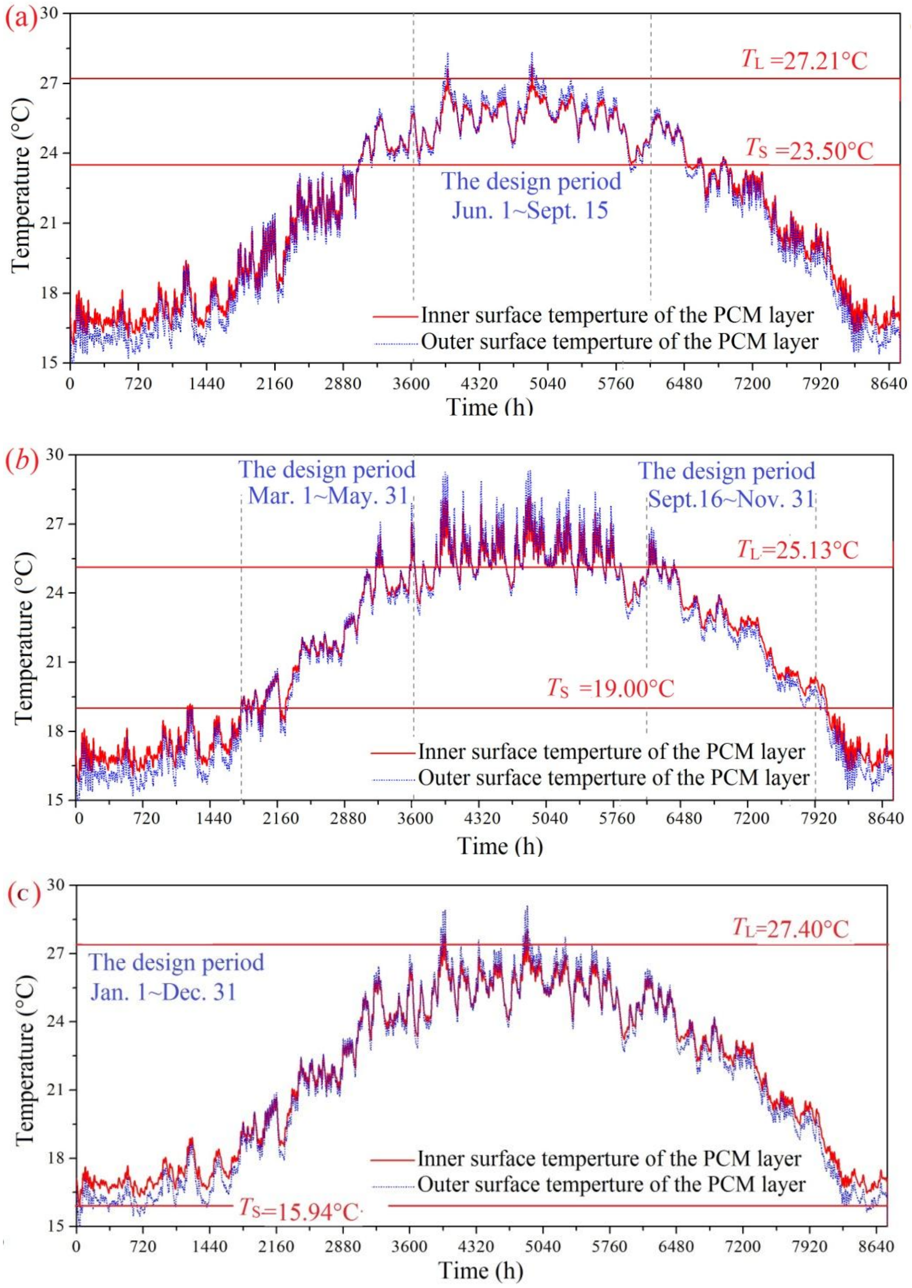


Figure 4-13 Variation of the surface temperatures for the PCM layer under the different phase-change occurrence design period: (a) Summer, (b) Transition seasons, and (c) All year

Table 4-6 Covering rate of wall surface temperature under different design periods of phase-change occurrence

Time period	PCM phase-change range		$\eta(T_{PCM,\ in})$	$\eta(T_{PCM,\ out})$
	T_S(°C)	T_L(°C)		
Summer	23.50	27.21	99.4%	96.7%
Transition seasons	19.00	25.13	91.5%	90.7%
All year	15.94	27.40	99.6%	96.1%

Meanwhile, in order to verify the PCM phase-change range accuracy gained from Equation. (3-15) and (3-16) under the different phase-change occurrence period, the solidus and liquidus temperatures in Table 3-2 is increased by 0.5 ℃ and reduced by 0.5 ℃ respectively. Figure 4-14 shows variation of the inner surface heat flows when solidus and liquidus temperature increased by 0.5 ℃ and reduced by 0.5 ℃. As shown in the figure, variation curves of inner surface heat flow are basically the same, when the liquidus temperature increased or decreased by 0.5 ℃, but it can be shown from the enlarged figure that both amplitude and value of inner heat flow have increased with liquidus temperature increased by 0.5 ℃. This phenomenon is resulted from that the liquidus temperature gained from Equation(3-16) has reached the high temperature value of the PCM layer and that the increase of liquidus temperature will reduce the phase-change latent heat per the temperature variation.

On the other hand, if liquidus temperature gained from Equation(3-16) has reduced by 0.5 ℃, inner surface heat flow variation becomes very severe in some time period (For example, 3900h ~ 4000h and 4800h ~ 4900h in Figure 4-14(a) and 3780h ~4140h and 4800h ~ 4900h in Figure 4-14 (b)). This phenomenon is resulted from that the liquidus temperature gained from Equation(3-16) has reached the high temperature value of the PCM layer exactly. The liquidus temperature reduction makes PCM become liquid state and lose phase-change property in some period, when PCM has the high temperature in the phase-change occurrence period as shown in Figure 4-14.

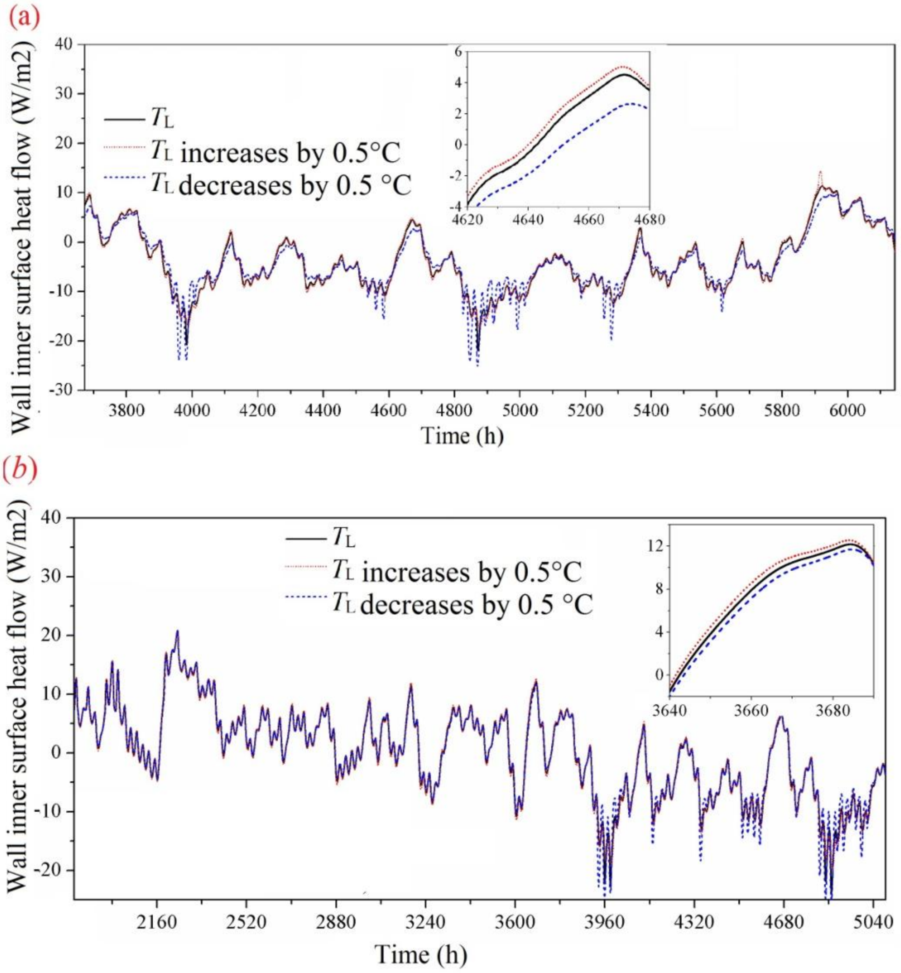


Figure 4-14 Variation of the inner surface heat flows under T_L, T_L increases and decreases by 0,5 0.5 ℃ with T_S keep a constant; (a) Summer and (b) transition season

In addition, Figure 4-15 shows variation of the inner surface heat flows under solidus temperature increased or decreased by 0.5 ℃. As shown in the figure, if solidus temperature gained from Equation. (3-15) has increased by 0.5 ℃, inner surface heat flow variation becomes very severe in some time period (For example, 3800h and 5900h ~ 6000h in Figure 4-15 (a) and 1880h ~ 2000h in Figure.4-15 (b)), owing to the fact that the increased solidus temperature cannot cover the low temperature value of the PCM layer.

On the other hand, if liquidus temperature gained from Equation. (3-15) has keep the same, the increased solidus temperature can also cover the low temperature value of the PCM layer, so variation curves of inner surface heat flow are basically the same if the solidus temperature increased by 0.5 ℃. However, due to solidus temperature reduced by 0.5 ℃, the phase-change latent heat per the temperature variation is reduced and thereby, both amplitude and value of inner flow heat flow with solidus temperature decreased by 0.5 ℃ are larger than those with solidus temperature keep the same.

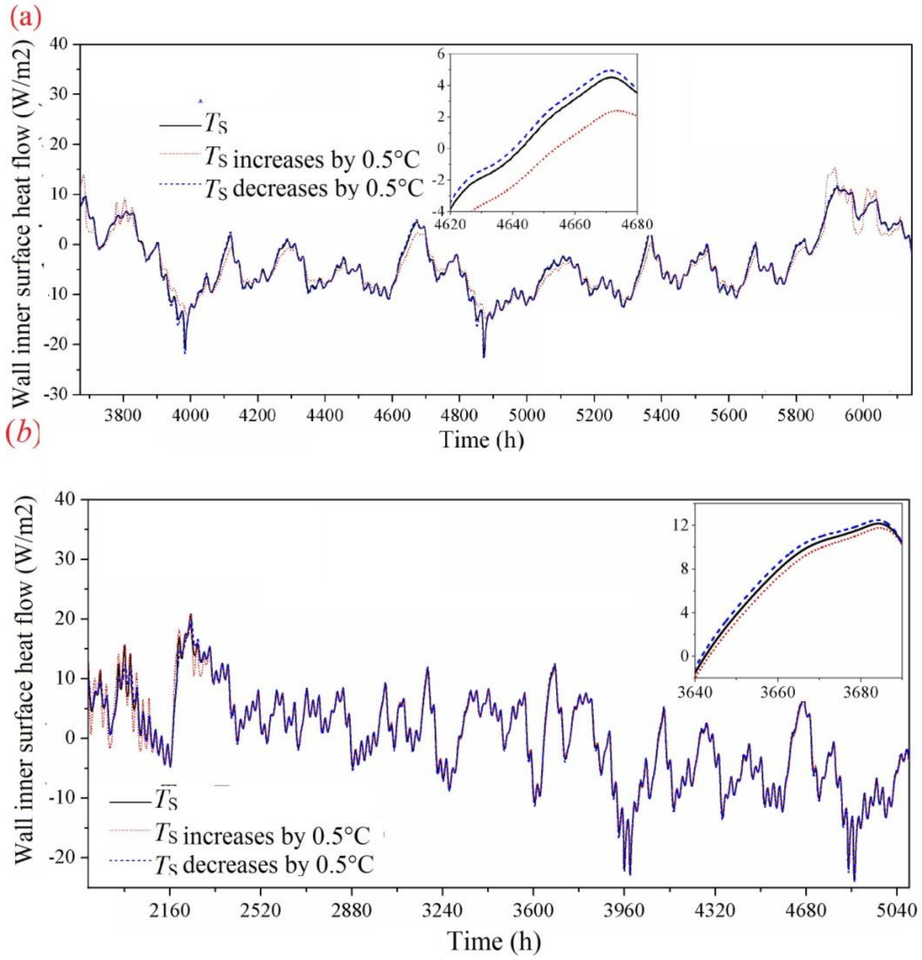


Figure 4-15 Variation of the wall inner surface heat flows under T_S, T_S increases and decreases by 0.5 ℃ with T_L keep a constant; (a) Summer and (b) transition season

From Figure 4-14 and Figure 4-15, no matter increase or reduction of liquidus temperature and solidus temperature gained from Equations(3-15 and 3-16), inner surface heat flow will happen the harmful variation, which indicates the solidus and liquidus temperatures of PCM gained from Equation. (3-15)and(3-16) are optimum. Meanwhile, the same rules are observed in the different phase-change occurrence design periods of summer and summer & transition seasons, which verifies the optimization of Equation. (3-15)and(3-16) under the different outdoor thermal environment conditions.

4.4.3 The selection of PCM phase-change range and verification of calculation method under the different location of the PCM layer

In order to make research on accuracy of theoretical calculation method for the PCM layer is done under the different location of the PCM layer, the PCM phase-change occurrence design period is summer (June. 1~Sep. 15). Outdoor climate condition is using the condition of Chengdu as shown in Figure 4-11. Indoor temperature is shown in Figure 4-12. The typical wall model in Figure.3-5. The thicknesses of the plaster layer, the PCM layer and the sintered brick layer are separately 20mm, 20mm and 220mm. The wall materials thermal performance property is same with what shows in Table 3-2. When make verification on calculation method of PCM phase-change range under the different location of the PCM layer, PCM layer is set in inner surface, middle surface and outer surface, namely L=0mm, L=110mm and L=220mm. Combined with above conditions and theoretical methods, Table 4-6 shows the theoretical values of PCM phase-change range under the different location of the PCM layer.

Table 4-7 Theoretical values of PCM phase-change range under the different location of the PCM layer

Cases	The location of the PCM layer	PCM phase-change range	
		T_S(°C)	T_L(°C)
1	Inner surface (*L*=0mm)	23.50	27.21
2	Middle (*L*=110mm)	15.99	30.52
3	Outer surface (*L*=220mm)	13.06	35.00

Figure 4-16 shows whole year variation of the surface temperatures of the PCM layer for the different locations of the PCM layer under the phase-change occurrence design period of summer & transition seasons. As shown in figures, under the phase-change occurrence design period, for PCM layer location of L=0mm and L=110mm, outer and inner surface temperature of PCM layer waves between solidus curve and liquidus curve, and just a small period is beyond this range. However, for the position of L=220mm, in a longer period, inner and outer surface temperature of PCM layer is beyond liquidus curve temperature, especially for PCM layer outer surface temperature fluctuation.

In addition, through the data processing, the covering rates of inner and outer surface temperatures are 98.4% and 97.3% for the location of L=0mm, 97.6% and 96.3% for the location of L=110mm and 94.7% and 92.7% for the location of L=220mm,as shown in Table 4-8, which shows the solidus and liquidus temperatures of PCM gained from Equation (3-15~3-16) can guarantee the PCM phase-change occurrence for the different locations of the PCM layer under the phase-change occurrence design period. Through the comparison of the phenomenon of L=0mm, 110mm and 220mm, the closer of PCM layer to wall inner surface, the smaller phase change range, the conclusion is same with what in Chapter 3.

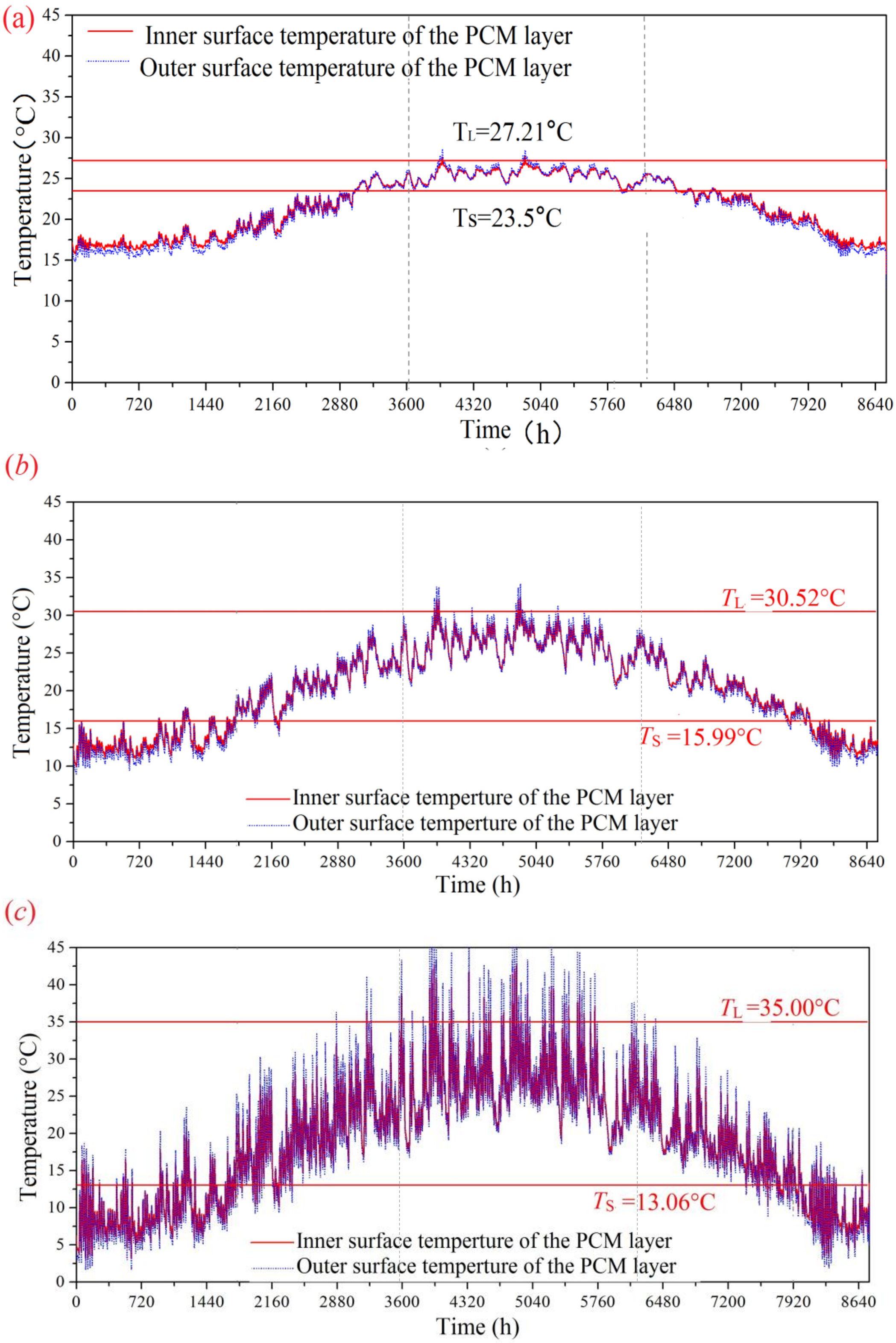


Figure 4-16 Variation of the surface temperatures for the PCM layer based on phase-change occurrence design period of summer under the different location of the PCM layer (a) L=0mm, (b) L=110mm, (c) L=220mm

Table 4-8 Covering rate of wall surface temperature under different location of the PCM layer

Cases	The location of the PCM layer	PCM phase-change range		$\eta(T_{PCM,\ in})$	$\eta(T_{PCM,\ out})$
		T_S(°C)	T_L(°C)		
1	Inner surface (*L*=0mm)	23.50	27.21	97.6%	96.3%
2	Middle (*L*=110mm)	15.99	30.52	98.4%	97.3%
3	Outer surface (*L*=220mm)	13.06	35.00	94.7%	92.7%

Figure 4-17 shows the comparison of variation of wall inner surface heat flow under liquidus temperature increased and decreased by 0.5 ℃ when the solidus temperature keep a constant. Figure 4-15 (a) is the variation for the location of PCM layer L=0mm. Figure 4-15 (b) is the variation for the location of PCM layer L=110mm. Figure 4-15 (c) is the variation for the location of PCM layer L=220mm. It can be found that when the PCM layer is located in wall inner surface (L=0mm), the increased and decreased liquidus temperature will enlarge amplitude and value of inner surface heat flow, while the decreased and the increased liquidus temperature will cause the severe variation of inner surface heat flow variation becomes very severe (For example, 1880h ~ 2000h in Figure 4-15(a)). However, When the PCM layer is located in the middle (L=110mm) and the wall outer side (L=220mm), three variation curves are in good agreement. This phenomenon may be resulted from their wide phase-change range of 15.99 ℃ ~30 ℃ and 13.06 ℃~35 ℃, on which the temperature arrange variation of 0.5 ℃ has only a small effect.

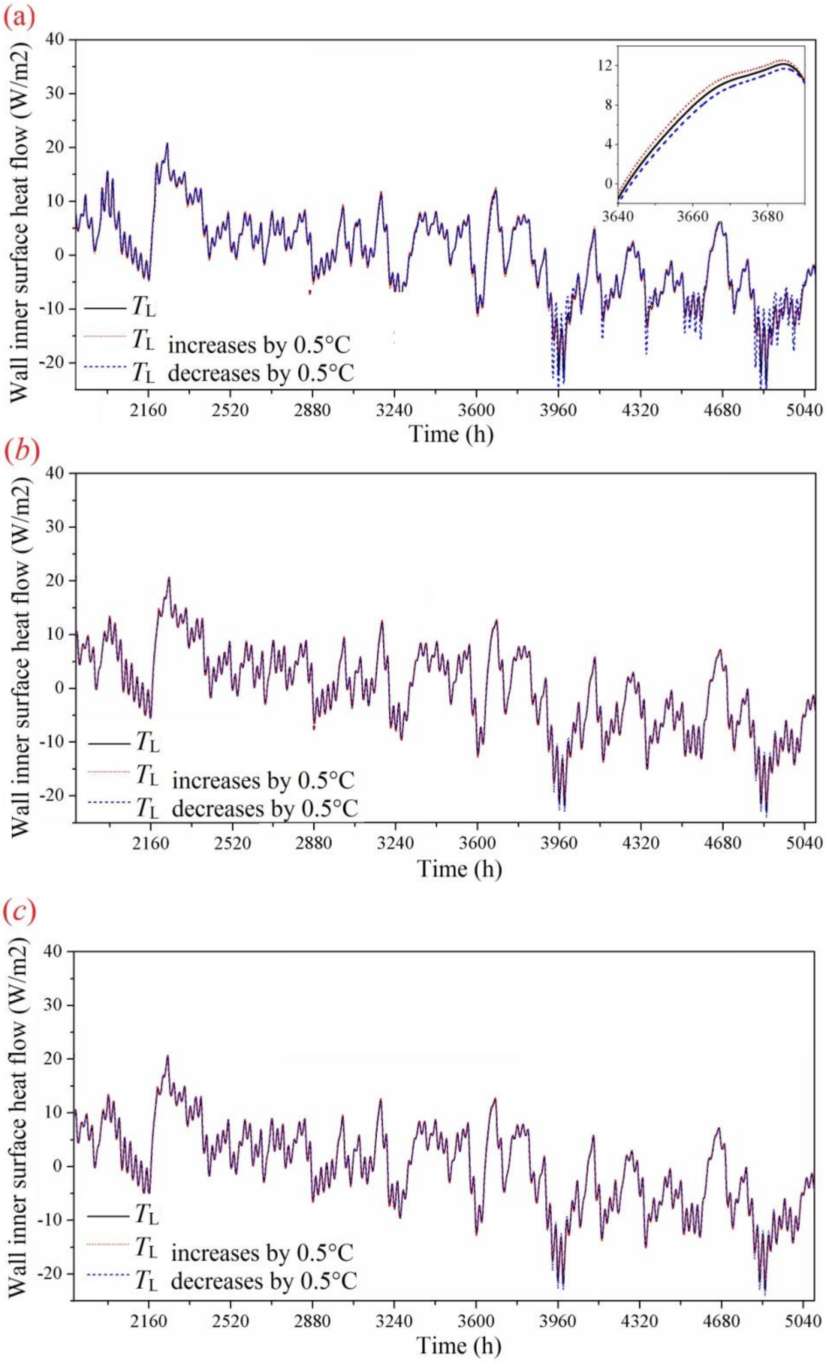


Figure 4-17 Variation of the inner surface heat flows under T_L, T_L increases and decreases by with T_S keep a constant; (a) L=0mm, (b) L=110mm, (c) L=220mm

Figure 4-18 shows the comparison of variation of wall inner surface heat flow under solidus temperature increased and decreased by 0.5 ℃ when the liquidus temperature keep a constant. Figure 4-18 (a) is the variation comparison for the location of PCM layer L=0mm. Figure 4-18 (b) is the variation comparison for the location of PCM layer L=110mm. Figure 4-18 (c) is the variation for the location of PCM layer L=220mm. It can be found that when the PCM layer is located in the internal wall side (L=0mm), the increased and decreased solidus temperature will enlarge amplitude and value of inner surface heat flow, while the decreased and the increased solidus temperature will cause the severe variation of inner surface heat flow variation becomes very severe (For example, 1880h ~ 2000h in Figure 4-18(a)). The variation curve for the PCM layer is located in the middle (L=110mm) and the external wall side (L=220mm) is same with that of liquidus temperature increased and decreased 0.5 ℃. However, compared with the Figure 4-17, we can find that the effect of liquidus temperature variation on inner surface heat flow is higher than that of solidus temperature.

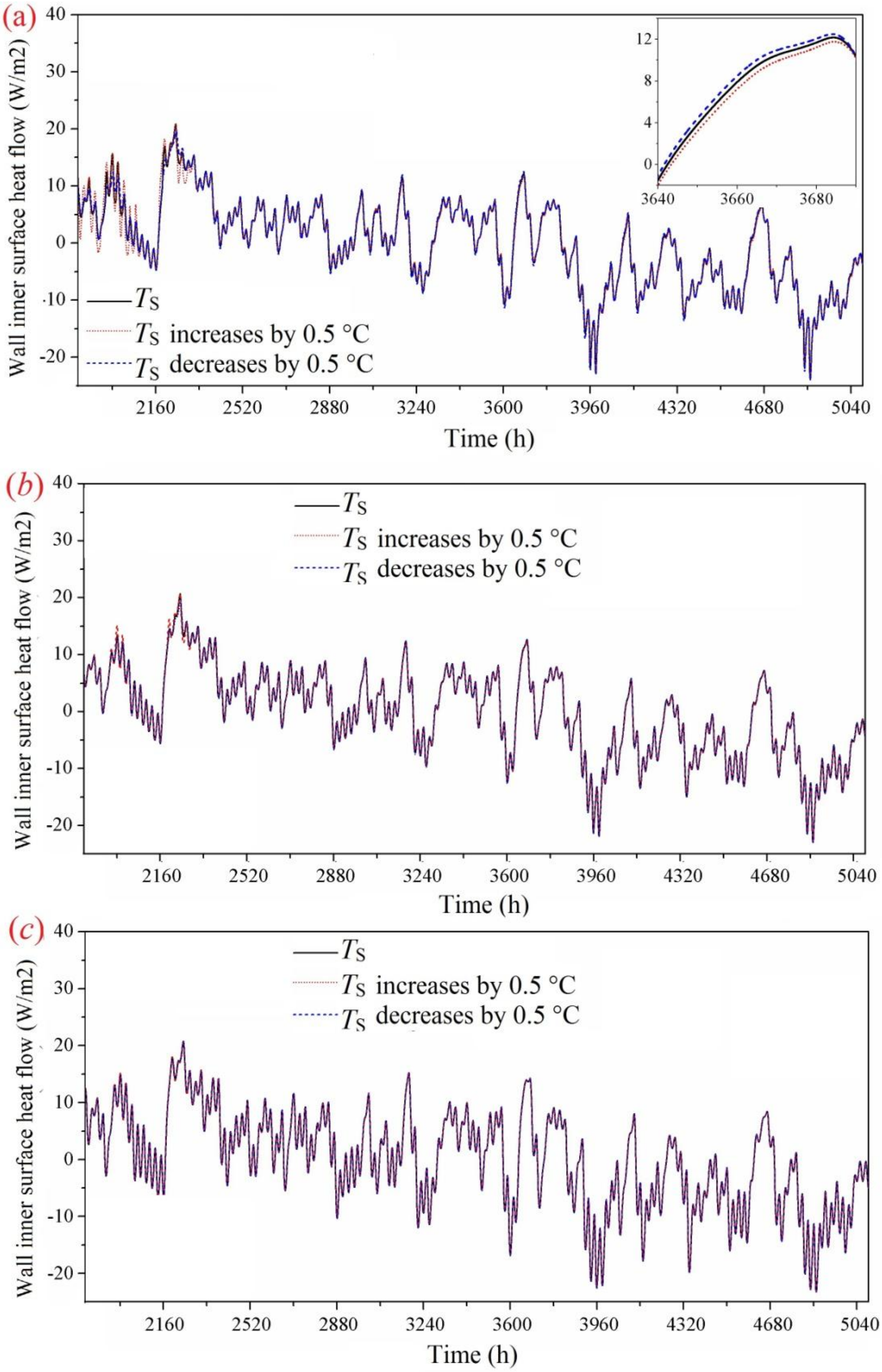
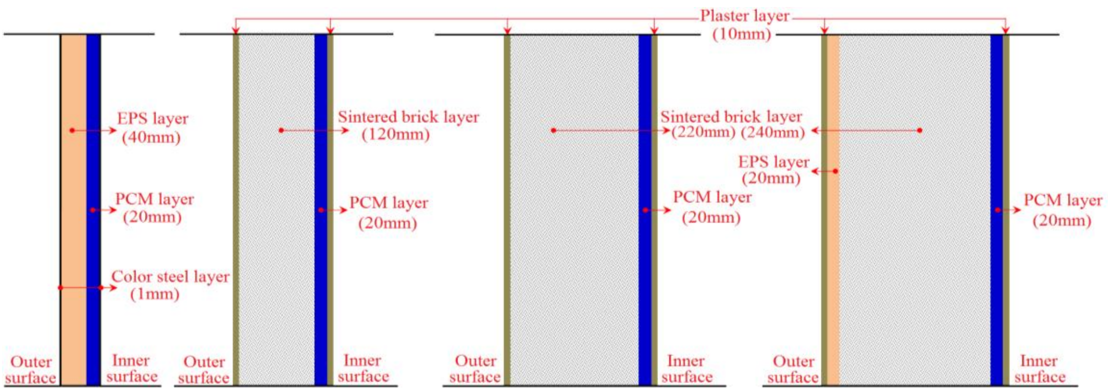


Figure 4-18 Variation of the inner surface heat flows under T_S, T_S increase and decreases 0.5 ℃ with T_L keep a constant; (a) L=0mm, (b) L=110mm, (c) L=220mm

4.4.4 The selection of PCM phase-change range and verification of calculation method under different wall structure

In order to make research on accuracy of theoretical calculation method for the PCM layer is done under the different location of the PCM layer, the PCM phase-change occurrence design period is summer (June. 1~ Sep. 15). Outdoor climate condition is using the condition of Chengdu as shown in Figure 4-11. Indoor temperature is shown in Figure 4-12. The wall structure are shown in Figure 4-19. Among which, Figure 4-19(a) shows an ultrathin wall of prefab houses, which is used widely as temporary shelter after a disaster or temporary offices for construction projects; Figure. 4-19 (b) shows a light-weight wall of a temporary house; Figure 4-19(c) and Figure 4-19 (d) denote the heavy-weight wall of residential and public buildings, respectively. The four wall structure have covered most of wall structure in China.



(a) Structure 1 (b) Structure 2 (c) Structure 3 (d) Structure 4

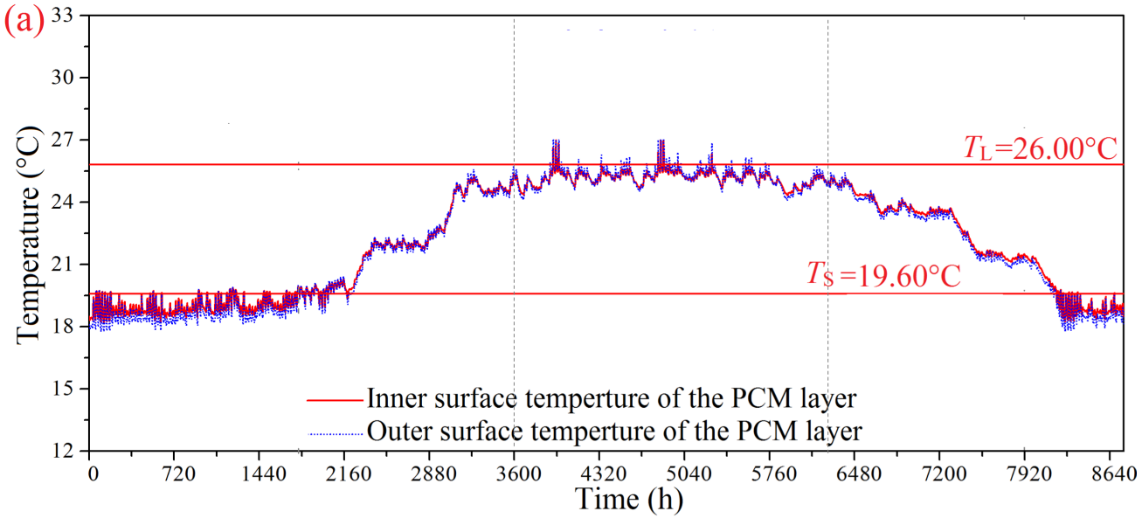
Figure 4-19 Four typical wall structure models

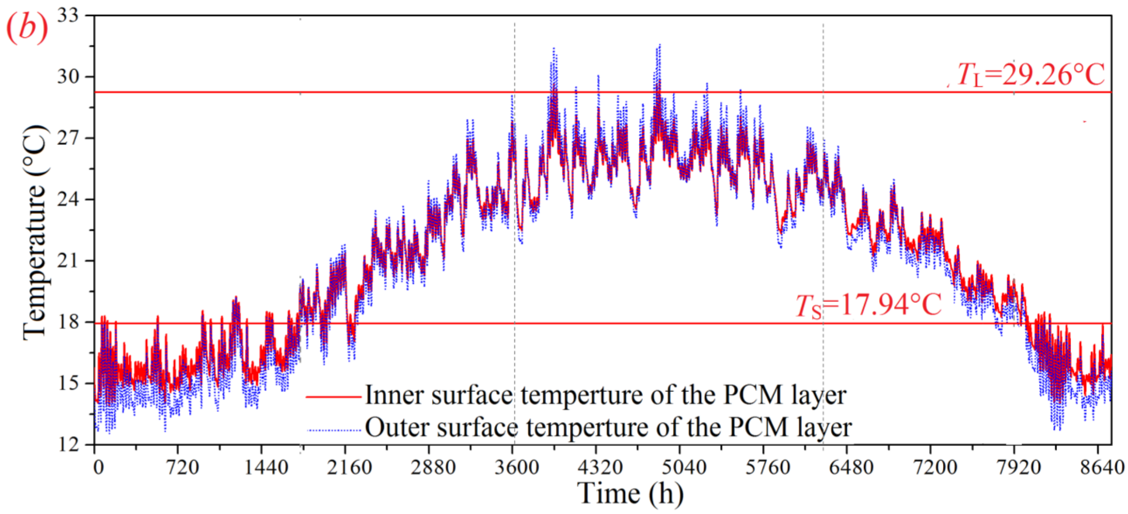
Combined with above conditions and theoretical methods, Table 4-9 shows the theoretical values of PCM phase-change range under the different location of the PCM layer. under the different wall structure models.

Table 4-9 Theoretical values of the PCM phase-change range under the different wall structure models

Cases	Wall models	PCM phase-change range	
		T_S(°C)	T_L(°C)
1	Structure 1	19.60	26.00
2	Structure 2	17.94	29.26
3	Structure 3	18.90	27.30
4	Structure 4	19.51	26.00

Figure 4-20 shows variation of the surface temperatures of the whole year for the PCM layer for four typical wall structure models under the phase-change occurrence design period of summer. As shown in figures, for four typical wall structure models, inner and outer surface temperatures of the PCM layer vary between liquidus and solidus temperatures basically, which shows the phase-change always occur in the phase-change occurrence period and thereby that PCM has the good effects of the phase-change heat storage. Through the data processing, the covering rates of inner and outer surface temperatures are 95.6% and 93.6% for Structure 1, 96.2% and 93.1% for Structure 2, 97.6% and 96.3%% for Structure 3 and 99.1% and 97.3% for Structure 4 as shown in Table 4-10, which shows the solidus and liquidus temperatures of PCM gained from Equation (3-15) and (3-16) can guarantee the PCM phase-change occurrence, no matter for the ultrathin wall (Structure 1), the light-weight wall (structure 2) or the heavy-weight wall (Structure 3 and 4)





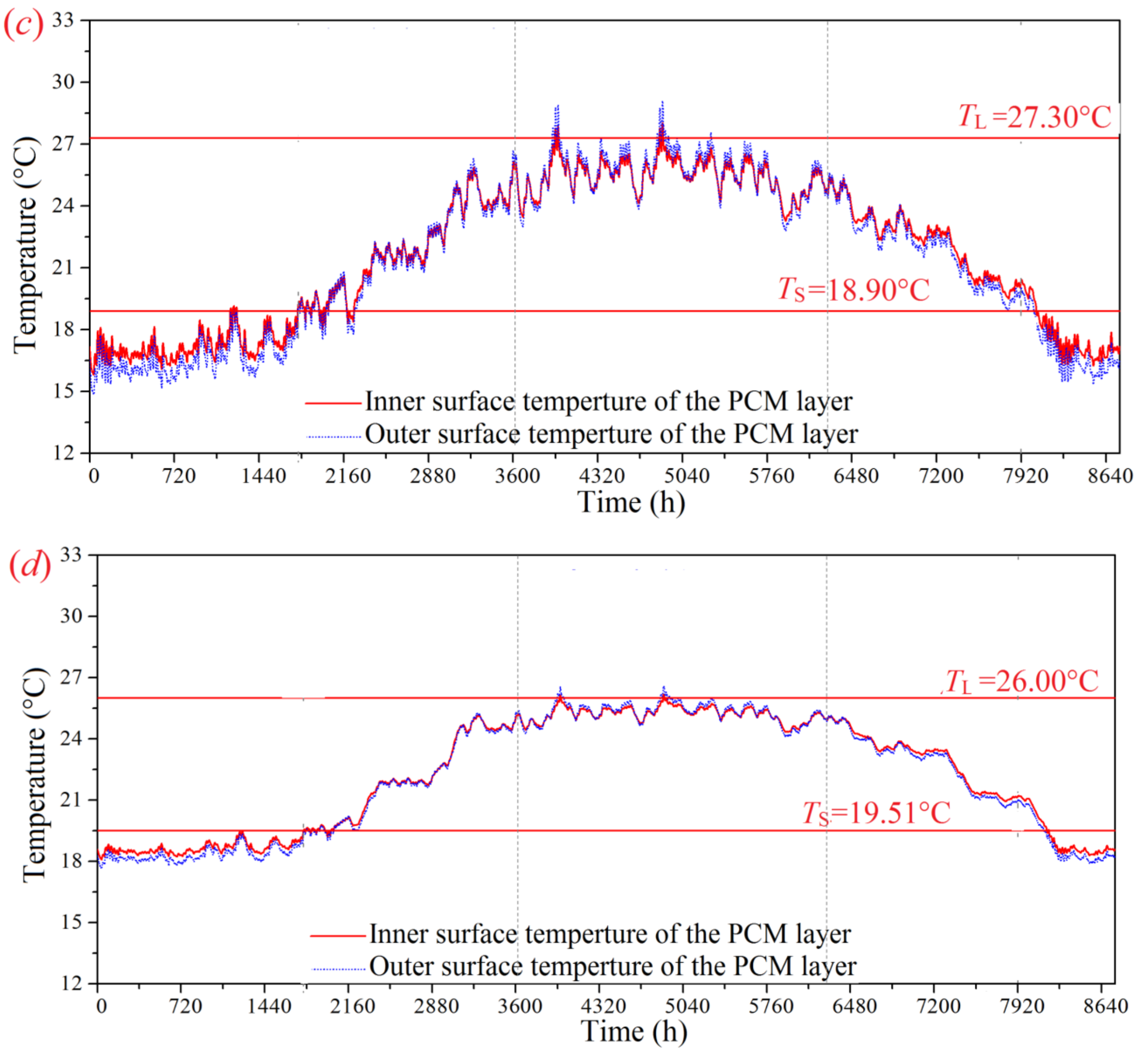
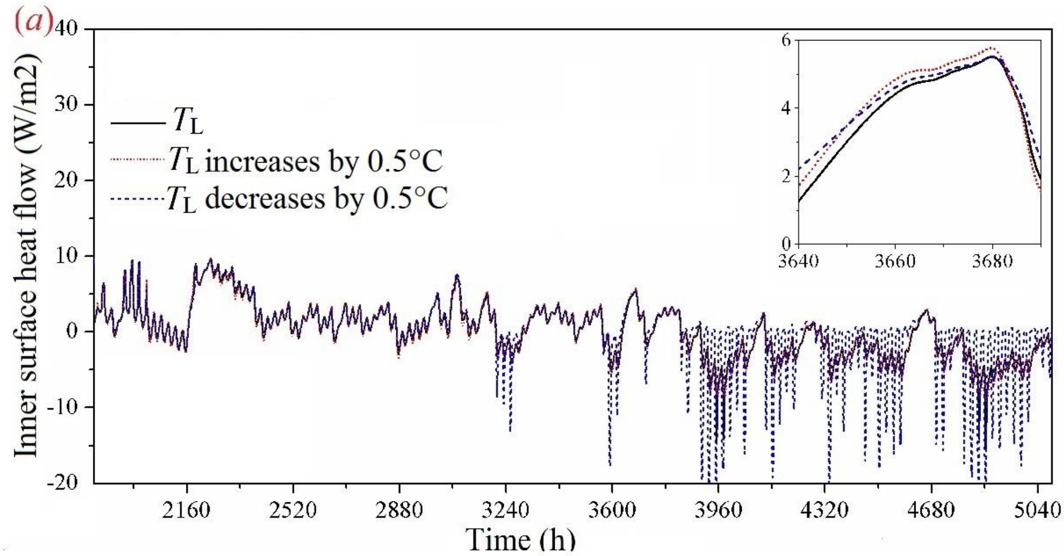


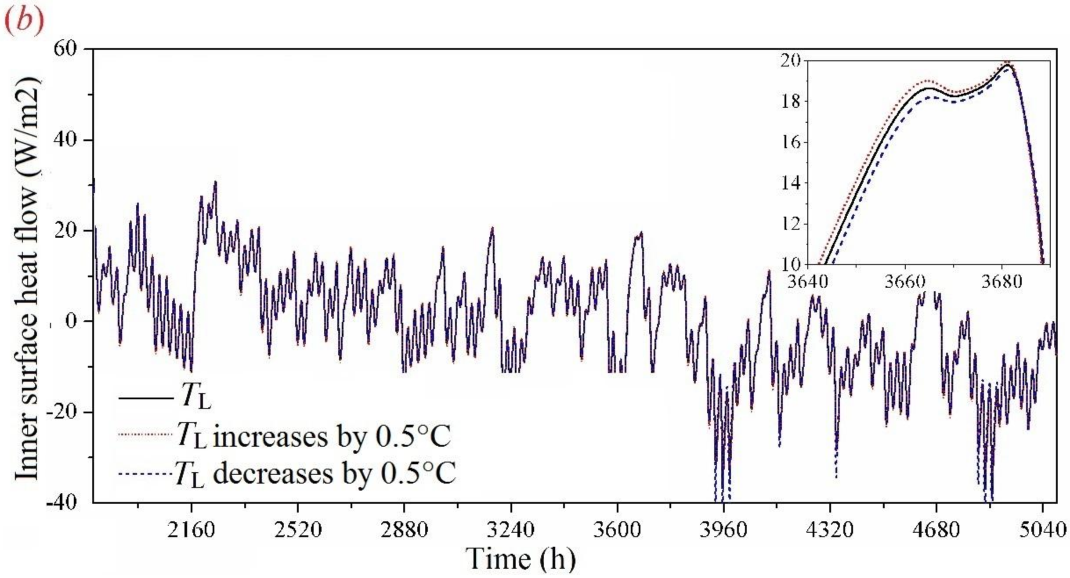
Figure 4-20 Variation of the surface temperatures for the PCM layer under the different wall structure (a) Structure 1, (b) Structure 2, (c) Structure 3 and (d) Structure 4 based on phase-change occurrence design period of summer

Table 4-10 Covering rate of wall surface temperature under different wall structure

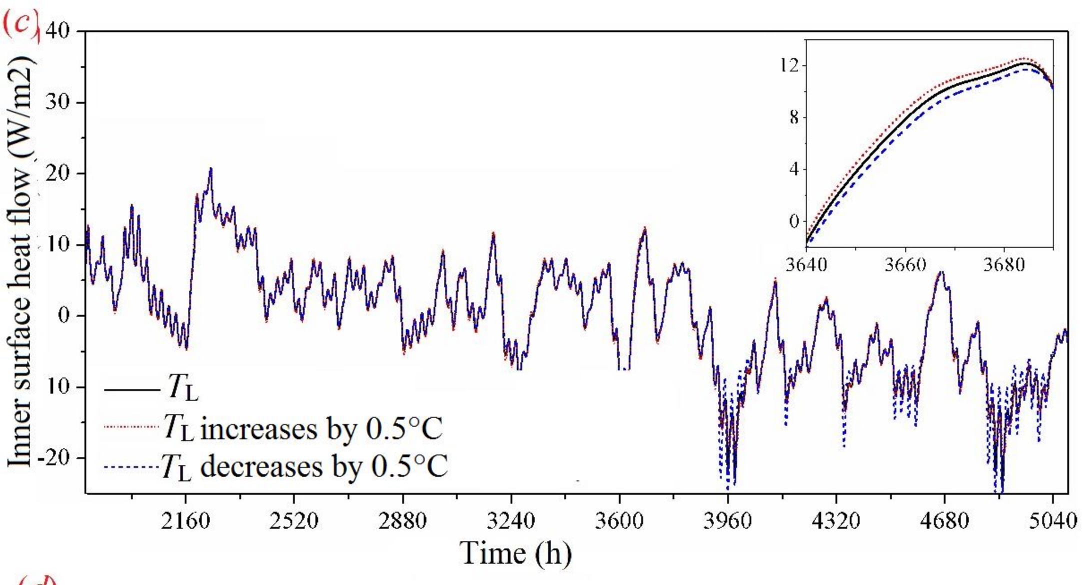
Wall structure	PCM phase-change rang		$\eta(T_{PCM,\ in})$	$\eta(T_{PCM,\ out})$
	T_S(°C)	T_L(°C)		
Structure1	19.60	26.00	95.6%	93.6%
Structure 2	17.94	29.26	96.2%	93.1%
Structure 3	18.90	27.30	97.6%	96.3%
Structure 4	19.51	26.00	99.1%	97.3%

Figure 4-21 shows the comparison of four typical structure wall inner surface heat flow variation under liquidus temperature increased and decreased by 0.5 ℃ when the solidus temperature keep a constant. It can be found that for Structure 1, increased or decreased the liquidus temperature by 0.5 ℃ will increase wall inner surface heat flow wave peak and valley, especially for the wave valley. For structure 2, the increase liquidus temperature increases the inner surface heat flow, however the decreased temperature deduced the inner surface heat flow, as shown in the Figure 4-21(b). For structure 3, the variation rule is same with what for structure 2. For structure 4, even it is also heavy-weight wall, the inner surface heat flow variation rule is different from structure 3. No matter the increased liquidus temperature and decreased liquidus temperature both increased wall inner surface heat flow.





(c)



(d)

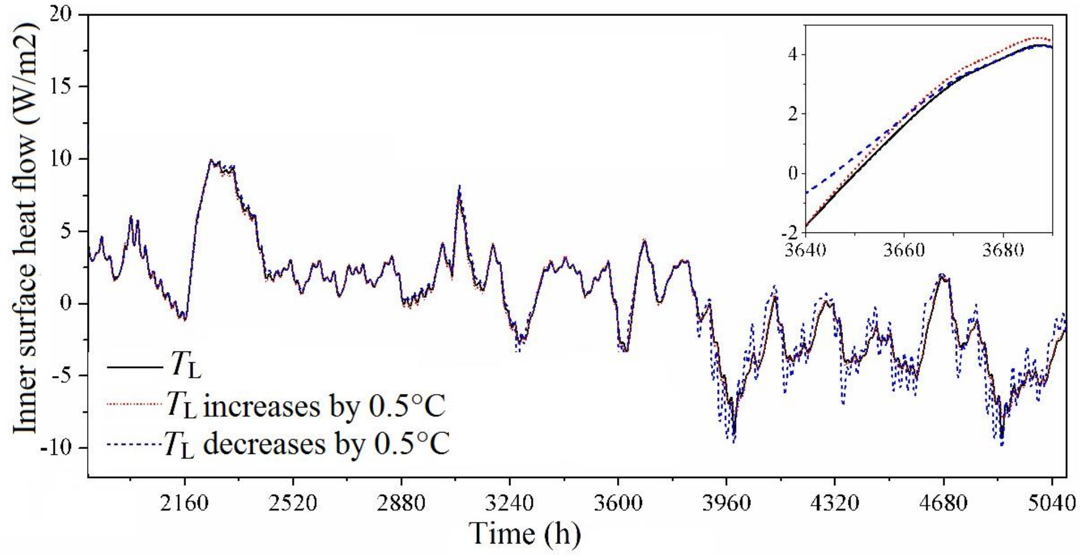
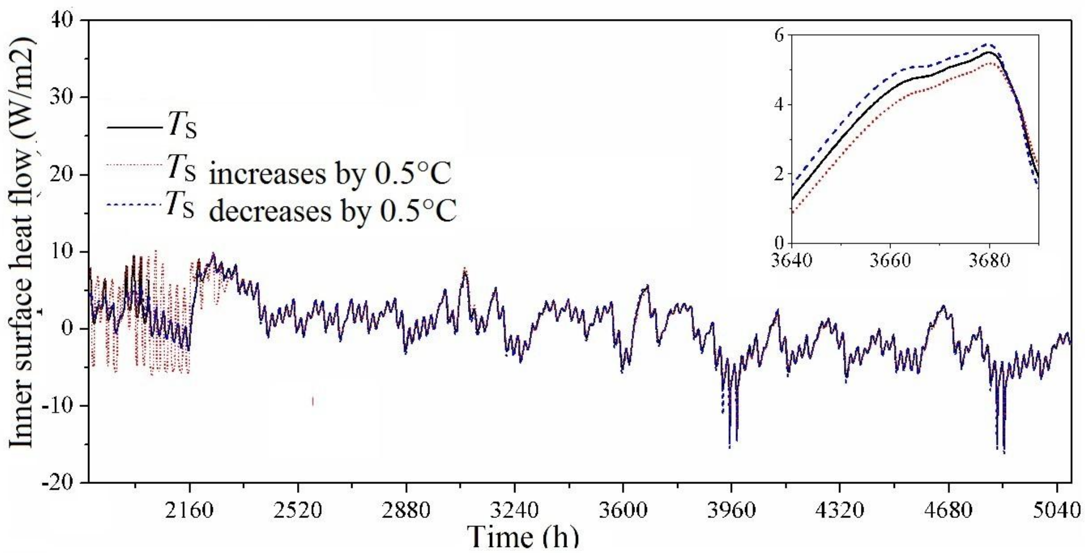


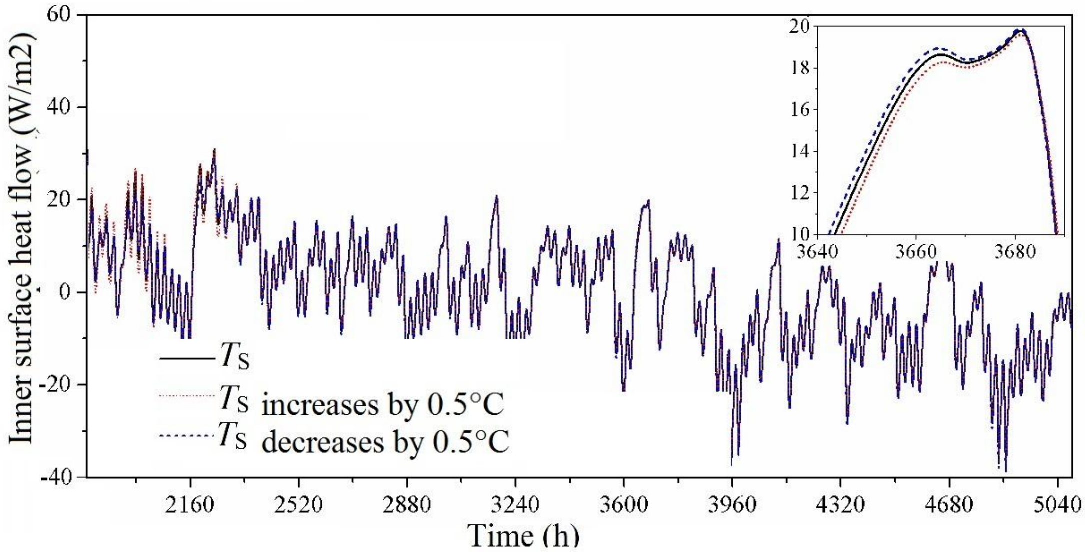
Figure 4-21 Variation of the inner surface heat flows under T_L, T_L increases and decreases by 0.5 ℃ with T_S keep a constant; (a)Structure 1, (b) Structure 2, (c) Structure 3 and (d) Structure 4

Figure 4-22 shows the comparison of four typical wall structure wall inner surface heat flow variation under solidus temperature increased and decreased by 0.5 ℃ when the liquidus temperature keep a constant. It can be found that solidus temperature increased by 0.5 ℃ has a bigger influence on wall inner surface heat flow than that of decreased by 0.5 ℃. In addition, increased the solidus temperature will lead to increase the wall inner surface heat flow, the result for decreasing solidus temperature is opposite for all wall structure. The influence of the variation of phase change temperature on wall inner surface heat flow for Structure 1 is biggest, then is Structure 4, Structure 3 and Structure 2.

(*a*)


Inner surface heat flow (W/m2)
Time (h)
T_S
T_S increases by 0.5°C
T_S decreases by 0.5°C
40
30
20
10
0
-10
-20
2160
2520
2880
3240
3600
3960
4320
4680
5040
6
4
2
0
3640
3660
3680

(*b*)


Inner surface heat flow (W/m2)
Time (h)
T_S
T_S increases by 0.5°C
T_S decreases by 0.5°C
60
40
20
0
-20
-40
2160
2520
2880
3240
3600
3960
4320
4680
5040
20
18
16
14
12
10
3640
3660
3680

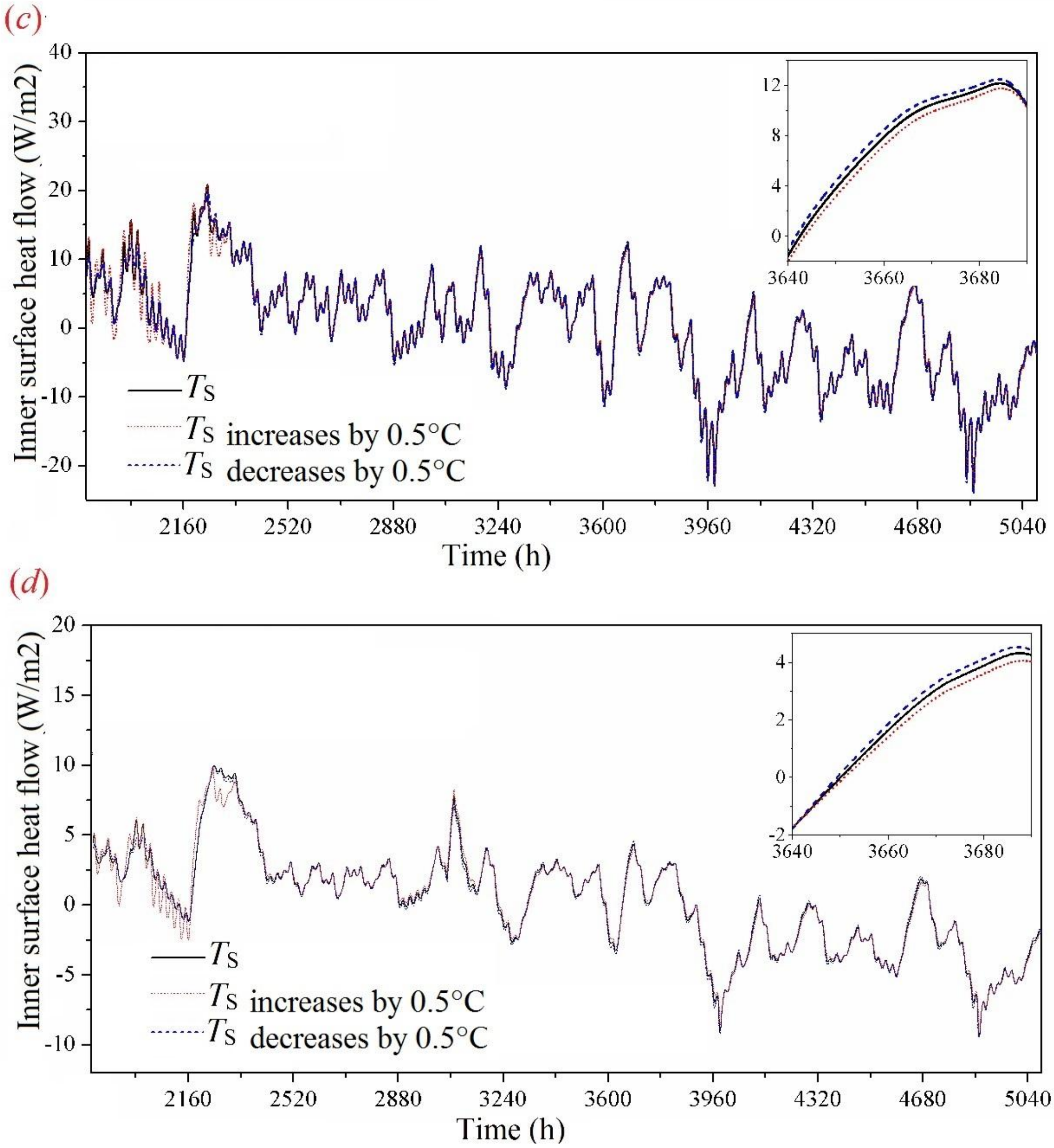


Figure 4-20 Variation of the inner surface heat flows under T_S, T_S increases and decreases by 0.5 ℃ with T_L keep a constant; (a) Structure 1, (b) Structure 2, (c) Structure 3 and (d) Structure 4

4.5 Summary

In this chapter, a heat transfer model of multi-layer wall integrated with PCM layer is established to make verification of theoretical calculation method of PCM layer phase change range in Chapter Three. The model is verified by literature data and experiment in Chengdu, China. The covering rate of the wall inner surface temperature is used to evaluating the accuracy of the calculating method. After that, selection of appropriate PCM phase change range and the verification is done under different design periods of phase-change occurrence, different position of the PCM layer in multi-layer wall, different multi-wall structure. Under three above verification cases, the PCM phase-change arrange obtained from the theoretical algorithm of Equation(3-15~3-16) can guarantee the phase-change occurrence in 90%~99% of the design periods, and thereby, PCM can improve the wall thermal properties by its heat-storage and discharge characteristics. On the other hand, weather the PCM phase-change arrange is reduced by 0.5℃ or increased by 0.5℃, the harmful variation will happen on the inner surface heat flow, which indicates that the PCM phase-change arrange obtained from the theoretical algorithm is optimum.

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Chapter Five: Case Study on Improvement of Walls Thermal Performance with PCMs layer in China

5.1 Introduction

China's building energy consumption accounts for about 25% of total energy consumption and the ratio will keep increasing because of construction industry has stepped into a quickly developing period. National building area in china will be twice in 2020 as that in 2000. In addition, according to reports, 52.1% world population live in urban environment[1]. In Europe and North America, urban population separately accounts for 72.9% and 82.2% of the national population. In China, the proportion increased from 26% to 52% from 1990 to 2011, and this tendency is keep increasing. It is estimated that 70% people will live in modern city[2]. Migration of population from villages to cities makes more demand for new buildings and public infrastructures and makes china become worldwide one of the biggest construction industry countries[3]. So far, the new construction area per year in china is above 20 billion square meters; however, above 95% of existing buildings with 40 billion square meter is higher energy consumption buildings[4], 80% of new construction building is also higher energy consumption buildings[5]. With the developing of life conditions, peoples demand for indoor thermal environment is also improving which increase sharply building energy consumption. Therefore, reducing building energy consumption and promoting building energy efficiency is imperative. In hot summer and cold winter region of China, the heat transfer conductivity of building exterior wall have lowered to 1.0 W/m2K[6] and in some other cities, the standard is more severe[7]. So energy conservation and improving energy efficiency has been one of strategic measures relieving energy shortage.

With the increase of building energy consumption and people's demand for indoor thermal comfort, the energy conservation for building envelops and building equipments has become more and more vital than before. Because of thermal resistance and heat capacity, temperature wave and heat flow wave will occur attenuation and delay effect when they pass building envelopes. So far, building envelops always adopt traditional organic thermal insulation materials for meeting the demand of building envelops energy saving. Even these materials has a low heat conductivity coefficient and can enlarge the thermal resistance. However, they have a low specific heat capacity value and most of them have fire safety problems and a short service life. Most of existing buildings use frame structure which are called infill walls and most of them are hollow, light-weight or middle-weight walls, especially concrete hollow block walls which lead to a smaller wall specific heat and a big amplitude and high frequency wall inner surface temperature and heat flow fluctuation with outdoor temperature variation. Meanwhile, above phenomena lead to indoor air-conditioning frequency start-stop or not running at a optimal case and then increase its running energy consumption.

Buildings power load varies greatly in different time of a day especially in hot summer. Generally, power load is big in daytime and low at night. So in order to meet the demand of power load in daytime, installed gross capacity of plant equipments must be increased. However, the power load is small at night, some plant equipments should be closed which lead to a low use ratio of generating plants and wasting of resources. In order to balance difference of grid on-peak load and off peak load, peak-valley electricity price is carried out in many cities namely the electricity price is different in daytime and night. The electricity charge of night in daytime is higher that at night which encourages using electric at night and reduce electricity consumption in daytime. This is helpful for peak load shifting in a certain. However, the electricity load is hard to be lowered obviously. The main raw material for electricity generation is fossil fuel[8]. In Europe, North America and China, fossil fuel using for electricity generation separately account for 69%, 68% and 93% of the whole generation raw materials[9]. So it is important that reducing energy consumption and cut off peak load using advanced technology.

PCM can absorb and exhaust heat with the occurrence of phase change and little temperature variation itself. PCM has a obviously higher latent heat value than sensible heat of traditional building materials. When PCM temperature increase to phase change temperature, phase change occurs and walls specific heat value increases obviously, which will decrease wall inner surface and indoor temperature fluctuation and lead to a better indoor thermal comfort, avoiding the frequency on-off of air conditioning equipments and keep them in a optimal running case then lower the energy consumption. In addition, the use of PCMs can increase building walls' heat capacity obviously, delay the wall inner surface temperature and heat flow peak time occurs and improve indoor thermal comfort and then save energy. Therefore, PCM layer using in building envelopes can shift air-conditioning load and improve indoor thermal comfort and prolong equipment life[10].

So in this chapter, under Chengdu climate, we firstly make research on the improvement effect of PCM layer on multi-layer wall thermal performance and energy conservation under different phase change range designing case, different location of PCM layer and different wall structures under air conditioning continue running mode. Then improvement effect on thermal performance of walls integrated with PCMs under the intermittent running of air conditioning in summer is also done.

5.2 Research on improvement of walls thermal performance with PCMs layer under the continues running mode of air conditioning

The climate condition of Chengdu have been introduced in Figure 4-11. Indoor temperature is set up as shown in Figure 4-12. And the simulation time is air conditioning keep running for 168 h. Wall inner and outer surface convective heat transfer coefficients are separately 19 W/(m2•K) and 8.7 W/(m2•K).

5.2.1 Analysis on improvement effect of multi-layer wall thermal performance with PCMs under different phase change design case

When making research on improvement effect of multi-layer wall thermal performance under different phase change occurrences design period, PCM is set up in wall inner surface, and the phase change range is set as Table 4-5. Figure 5-1 shows the wall inner surface temperature variation situation with time when PCM is set up in the inner surface of wall (namely L=0mm),and the phase change range is designed under different phase change occurrence design case in different seasons. It can be found that wall integrated PCM layer can lower inner surface temperature fluctuation obviously; however under different outdoor climate condition and phase change design case, the improvement effect of PCM layer on wall thermal performance have big difference.

From Figure 5-1 (a), it can be found that in summer, wall inner surface temperature fluctuation is the smallest when the phase change occurrence period is designed according summer climate, Compared with wall without PCM layer, wave peak decrease rate of wall inner surface temperature is up to 82.8%, and peak value delayed 7.667h. Secondly, under the whole year design case, compared with wall without PCM layer, wave crest decrease rate of wall inner surface temperature is up to 65.7%, and peak value delayed 4.56h; The worst improvement effect is when PCM phase change range is designed according transition season, and the wave crest decrease rate of wall inner surface temperature is just 24.1%, peak value delayed 1h;

The reason is that according summer climate, and a whole-year design case all cover the summer condition, PCM has obviously exothermic and heat storage effect of phase change. And when designed according transition season, PCM is always liquidus statue and then has worse improvement effect. In addition, according comparison among designing PCM phase change region in summer and a whole-year condition, just in summer case, PCM has the smallest phase change region, so it has the biggest phase change exothermal and heat storage capacity by unit temperature change, and wall biggest inner surface temperature decrease rate;

The similar volatility phenomenon can be found from Figure 5-1(b). In transition season, the using of PCM layer in multi-layer walls have the phase change occurs and cut down the inner surface temperature peak value. The peak value decrease rate is biggest when designing phase change range according transition season climate, other designing case sequence of influence effect from big to small is designing according a whole year climate and summer climate. However, for the case designing PCM phase change range according summer condition, just at partly higher temperature period, PCM has the phase change effect, such as 72h and 96h.

From Figure 5-1 (c), it can be found there is a better temperature peak decrease rate in winter when designing phase change range according a whole year climate because it covers winter when designing PCM phase change range; other conditions do not cover winter, PCM always keep solidus statue and cannot store latent heat. In this situation, wall integrated with PCM layer just add a layer to wall, there is just a little decrease effect.

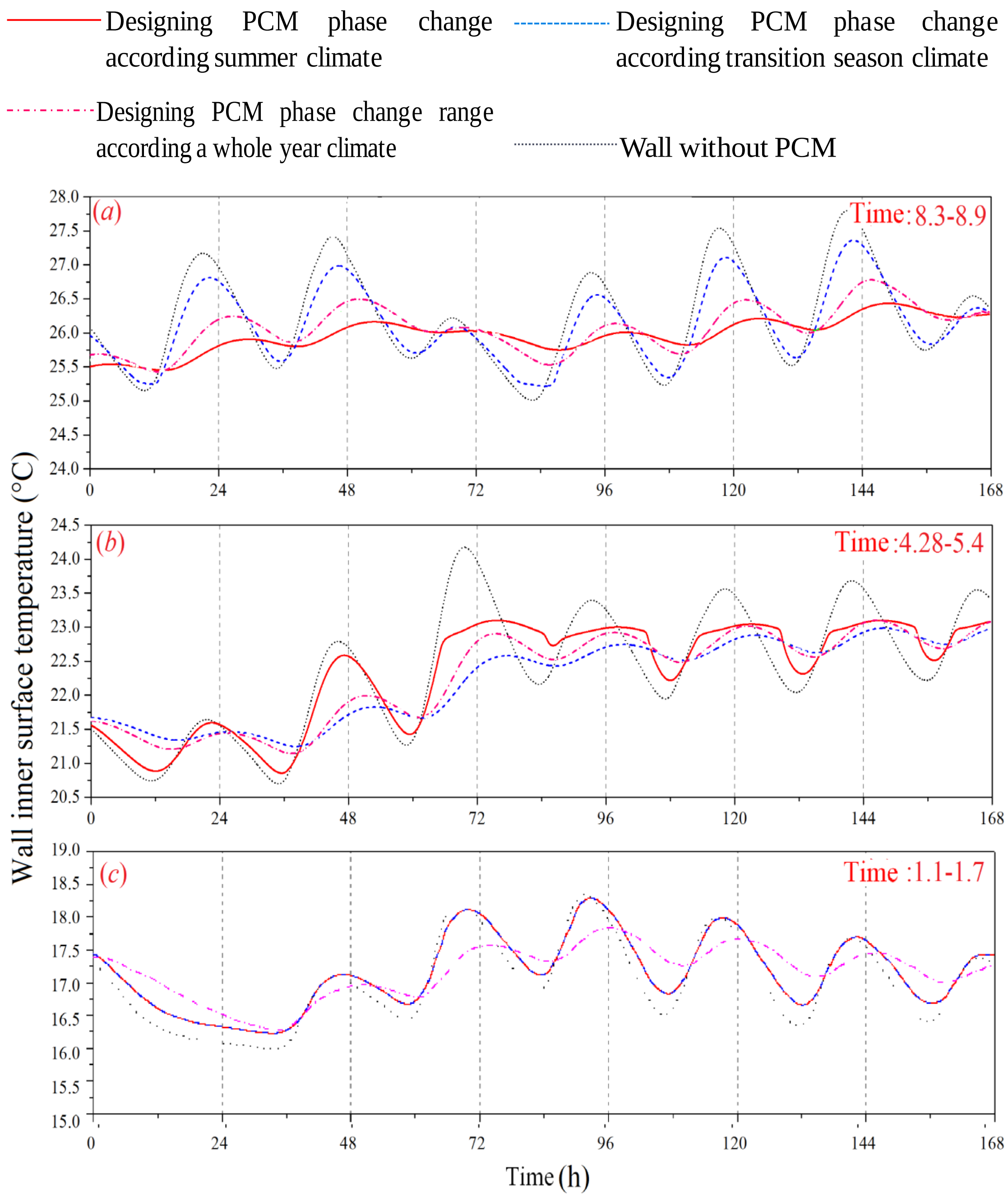

Figure 5-1 Variation of inner surface temperature under the different phase-change occurrence design periods (a) Typical summer climate, 8.3~8.9 (b) typical transition climate, 4.28~5.4 (c) typical winter climate, 1.1~1.7

Figure 5-2 shows variation of inner surface heat flow with time under the different phase-change occurrence design when PCM layer is set up on wall inner surface (namely L=0mm). From Figure 5-2(a), it can be found that in summer, wall inner surface heat flow has the biggest wave peak decrease effect and longest delay time, when designing PCM phase change range according summer climate. Compared with wall without PCM layer, wall inner surface heat flow wave peak decrease rate is up to 82.9%; then is when designing PCM phase change range according a whole-year condition, the inner surface heat flow wave peak decrease rate is 65.9%. and the worst effect is when designing PCM phase change range according transition season climate, the inner surface heat flow wave peak decrease rate is 24.1%.

From Figure 5-2 (b) is the variation of inner surface heat flow with time in typical transition climate. It is easy to be found that when designing PCM phase change range according transition season climate condition, wall inner surface heat flow has biggest decrease effect of wave peak and longest delayed time. Following that designing PCM phase change range according summer climate condition. However, from 60h, the wall surface heat flow decrease rate is increased greatly because of the higher outdoor temperature.

From the Figure 5-2(c), it can be found that in winter, when designing PCM according a whole-year climate condition, PCM has a certain exothermal and heat storage effect. The influence theory of wall inner surface is same with inner surface temperature wave peak and not be repeated here.

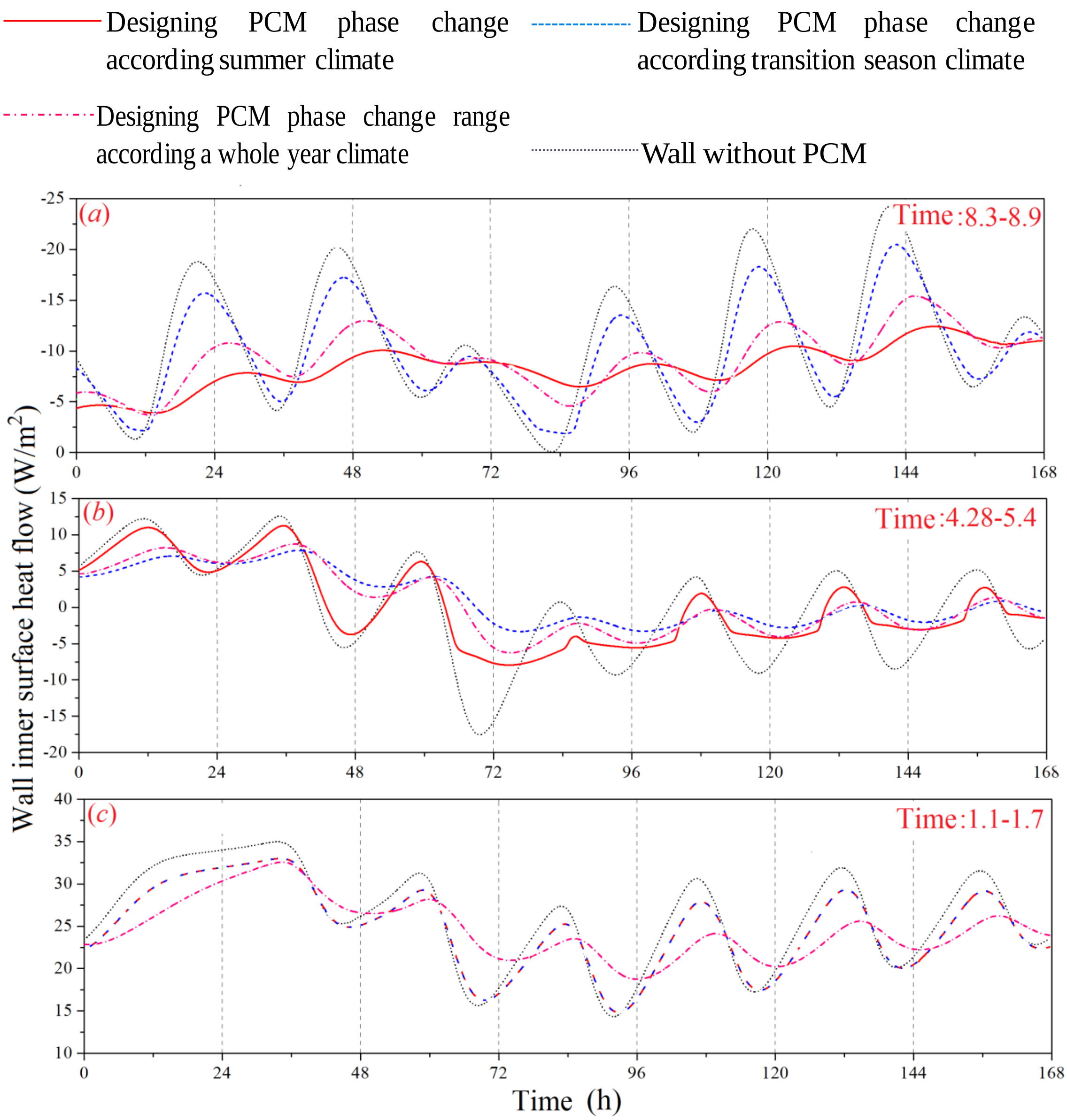

Figure 5-2 Variation of inner surface heat flow under the different phase-change occurrence design periods (a) Typical summer climate, 8.3~8.9 (b) typical transition climate, 4.28~5.4 (c) typical winter climate, 1.1~1.7

Compared Figure 5-1 and Figure 5-2, we can found that the variation rule of wall inner surface temperature is accordance with that of heat flow. The reason can be got according wall inner surface convective heat transfer calculation formula:

$$q = h_{in}(T_{l,in} - T_{in}) \quad (5\text{-}1)$$

When indoor air-conditioning heating, indoor temperature T_{in} and inner surface convective heat transfer coefficient h_{in} is constant, the variation rule of inner surface temperature and heat flow is similar which can be got from equation(5-1)

Figure 5-3 shows comparison of the average heat flow values under the different phase-change occurrence design periods when PCM is set in wall inner surface (namely L=0mm). Make the wall without PCM as base, when in summer, inner surface heat flow decrease rate is highest when PCM phase change range is designed according summer climate condition, up to 25.9%; In transition season, the highest value occurs when PCM phase change range is designed according transition season climate condition, which is up to 18.7%. In winter, the highest value occurs when PCM phase change range is designed according a whole year climate condition, which is up to 5.4%; however, when considering a whole-year, the best energy saving effect occurs when designing PCM phase change range according transition season climate condition. However, the difference between four case is small.

On the other hand, even when designing PCM phase change range, some season is not included, at the season, inner wall surface also has a higher averagely heat flow decrease rate, such as when phase change range designed according transition season climate condition, the average heat flow decrease rate is up to 24.9% in summer; and when phase change range designed according summer climate condition, the average heat flow decrease rate is 18.0% in transition season; there are two reason for this phenomenon: (1) wall integrated PCM layer can add the wall thickness, so that it can reduce wall inner surface heat flow. (2) Even when designing PCM phase change range, some season is not considered, however, it is included in final design.(as shown in Figure 4-14).

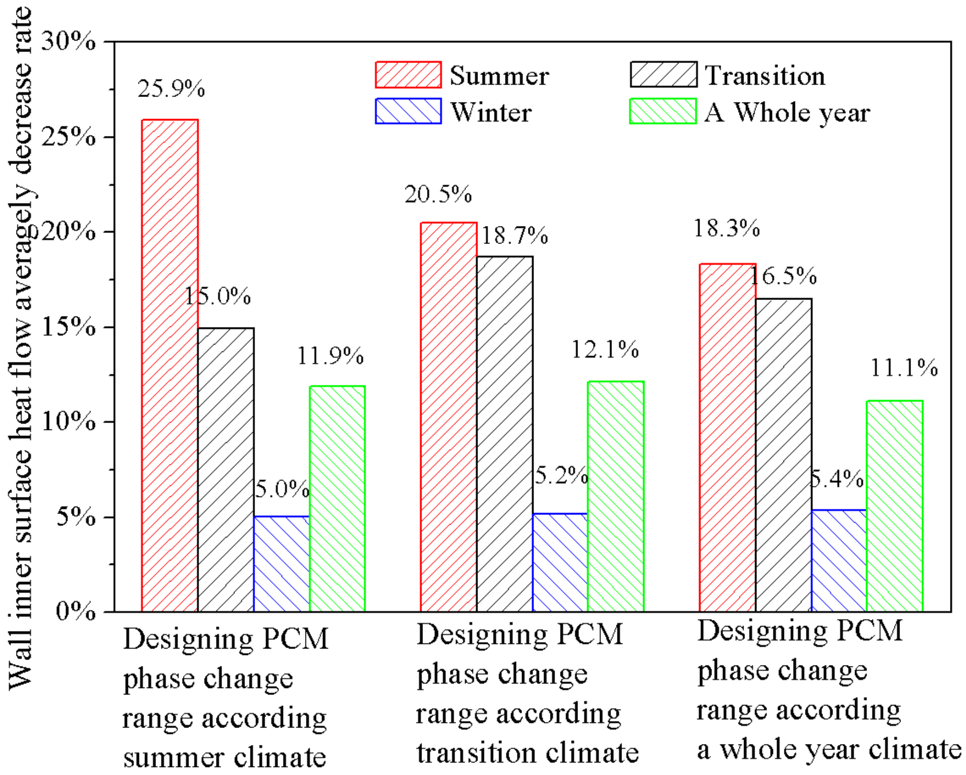

Figure 5-3 Comparison of the average heat flow decrease rate under the different phase-change occurrence design periods.

Table 5-1 shows the quantitative index of improvement effect of PCM layer on wall thermal performance according different PCM phase change range designing condition at the base of wall without PCM layer. So when PCM design time condition cover a certain period, wall inner surface temperature and heat flow amplitude both have a big decrease.

Some notes for this section:

(1)Above conclusions are all based on the climate of Chengdu, some certain wall structure and property, given PCM property(not including liquidus and solidus temperature) and fixed PCM layer location, so the conclusion has some limitations, even though it provide significance meaning for engineering practice.

(2)This chapter set up for designing case, and is partial to divide by season based on time. However, in practice, designing period can be selected according local improvement season demand.

Table 5-1 improvement effect of PCM layer on wall thermal performance under different PCM phase change season designing case

Case	Improvement factor	PCM phase change range designing period		
		summer	Transition season	A whole year
Summer	Temperature amplitude decrease rate	82.80%	24.10%	65.70%
	Temperature amplitude delay time(h)	7.67	1	4.68
	Heat flow amplitude decrease rate	82.90%	24.10%	65.70%
	Heat flow average decrease rate	25.90%	20.50%	18.30%
Transition season	Temperature amplitude decrease rate	52.00%	77.80%	67.20%
	Temperature amplitude delay time(h)	4.32	5	4
	Heat flow amplitude decrease rate	48.40%	73.10%	60.60%
	Heat flow average decrease rate	15%	18.70%	16.50%
Winter	Temperature amplitude decrease rate	11.80%	11.80%	50.90%
	Temperature amplitude delay time(h)	1	1	3.67
	Heat flow amplitude decrease rate	11.80%	11.80%	50.90%
	Heat flow average decrease rate	5.00%	5.20%	5.40%
The whole year	Heat flow average decrease rate	11.90%	12.10%	11.10%

5.2.2 Analysis on improvement effect of multi-layer wall thermal performance with PCMs under different location of PCM layer

When PCM layer is added to different location of the wall, research on the improvement effect of PCM on multi-layer wall thermal performance is made in this section. And phase change range of PCM is designing according summer climate, PCM phase change range is set as Table 4-7. Figure 5-4 give the variation situation of wall inner surface temperature with time when the PCM layer is under different location. It can be found that when PCM is located in different location, PCM all can improve wall inner surface temperature stability obviously. In addition, from figure 5-4, it can be found that the closer the PCM layer to wall inner surface, namely the smaller L is, the smaller wall inner surface temperature fluctuation. And in winter (Figure 5-4c), PCM always keep liquid statue when PCM phase change range is designed according summer and transition season climate condition, so the improvement effect of inner surface temperature stability are basically same in different season.

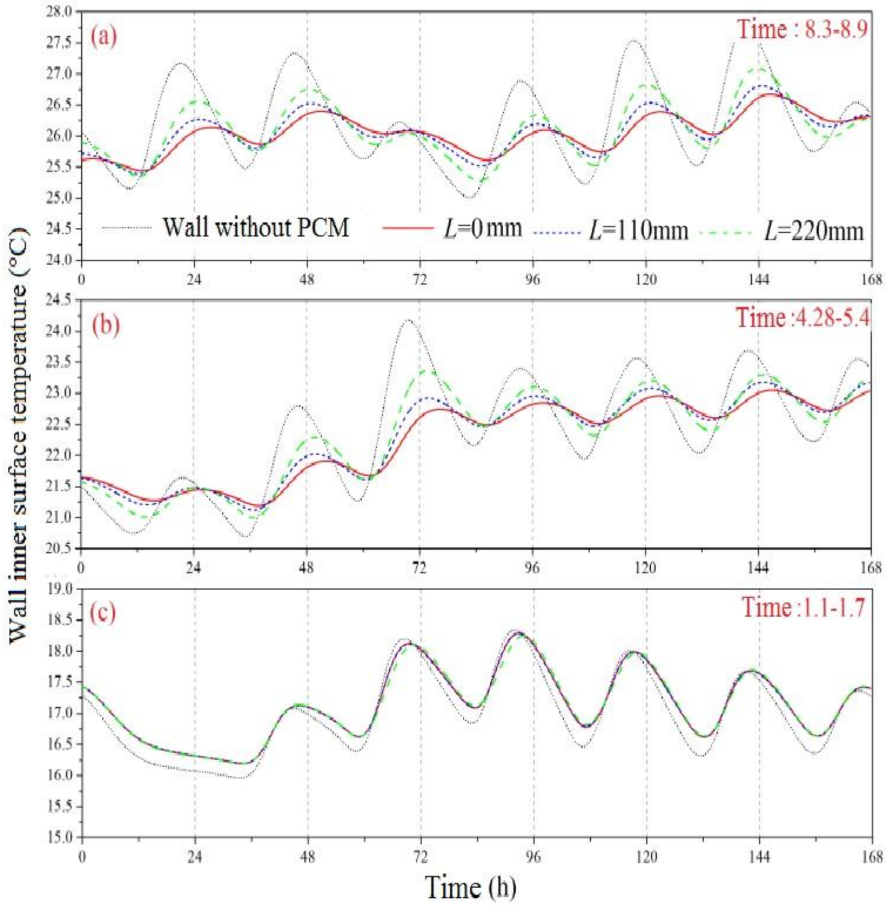

Figure 5.4 Variation of inner surface temperature under the different locations of the PCM layer (a) Typical summer climate, 8.3~8.9 (b) typical transition climate, 4.28~5.4 (c) typical winter climate, 1.1~1.7

Figure 5-5 gives the variation situation of multi-layer wall integrated PCM inner surface heat flow with time under different location when phase change range is designed according summer climate condition. It can be found that when PCM is located in different location, PCM layer all can lower the heat flow peak value obviously and delays the peak value occur. So PCM layer in multi-layer wall is helpful for lowering electricity consumption peak value caused by air-conditioning cooling and heating. In addition, from Figure 5-5(a) Figure 5- 5(b), it can be found that when the closer PCM layer to wall inner surface, namely the smaller L is, the smaller wall inner surface heat flow. And in winter, PCM is always liquidus when PCM phase change range is designed according summer climate condition, the effect of exothermal and heat storage of PCM layer is not very well.

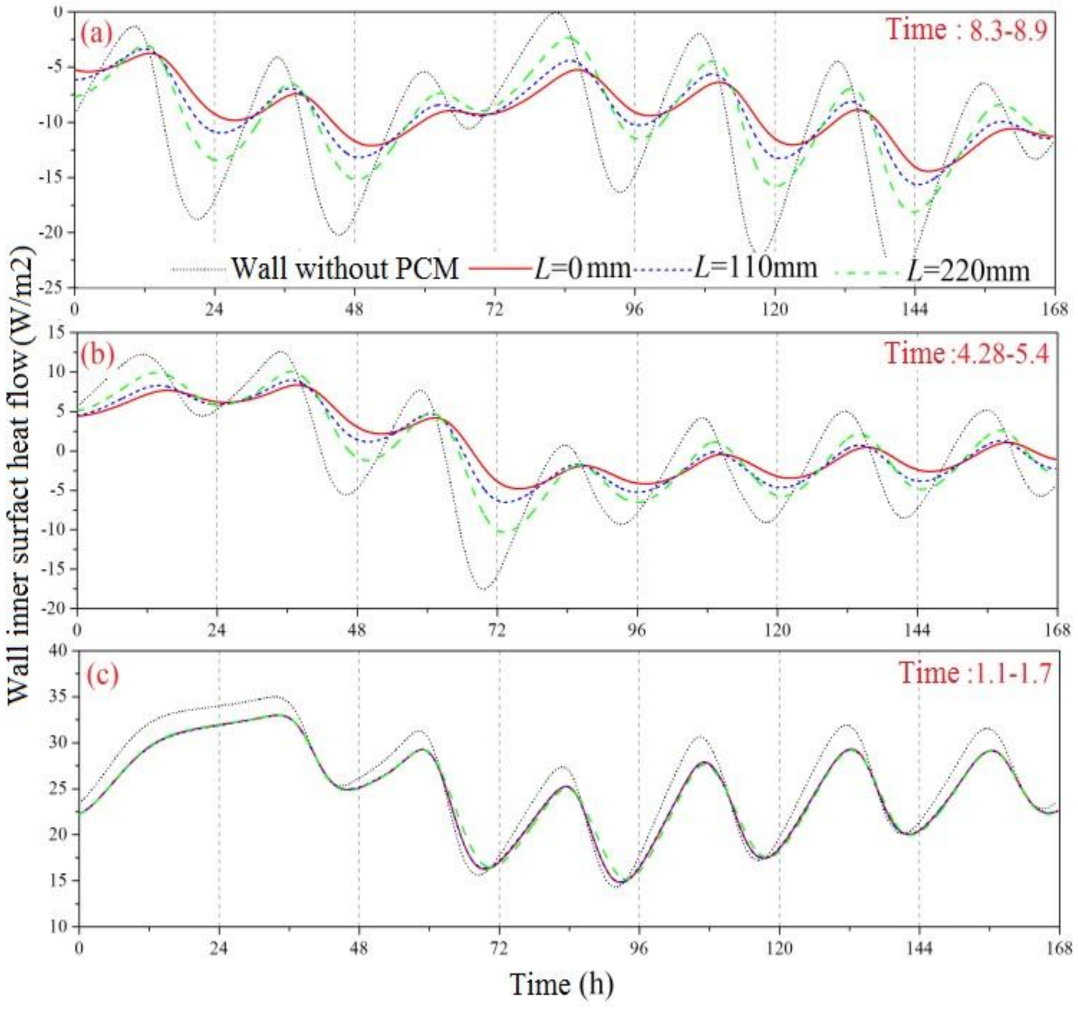

Figure 5-5 Variation of inner surface heat flow under the different locations of the PCM layer (a) Typical summer climate, 8.3~8.9 (b) typical transition climate, 4.28~5.4 (c) typical winter climate, 1.1~1.7

From Figure 5-4 and 5-5, we can found that when phase change occurs, the smaller the L is, the better the effect of improvement wall thermal performance. The reason is that the closer of PCM layer to wall inner surface, the smaller of PCM phase change range. And in the same phase change latent heat, the bigger phase change latent heat unit temperature change, the more helpful for improving wall thermal performance.

Figure 5-6 shows in different PCM layer location, wall integrated with PCM inner surface heat flow decrease rate according different season. For three different condition, When PCM layer is located in wall inner surface, it is best for inner surface heat flow decay. When L is increased from 0 to 110 mm, wall inner surface averagely heat flow decrease rate decreased 0%~7.5%. In addition, the influence of PCM layer location on inner surface heat flow averagely decrease rate is smallest in winter between 5.0% and 5.2%. The value in summer is biggest, vary from 20.5% to 11.3% from L=0mm to L=220mm. So with the scope of close to wall inner surface, changing location properly can reduce the influence on wall thermal performance; that is in the location close to wall inside, the influence on wall thermal performance can be accepted if PCM layer move outside properly.

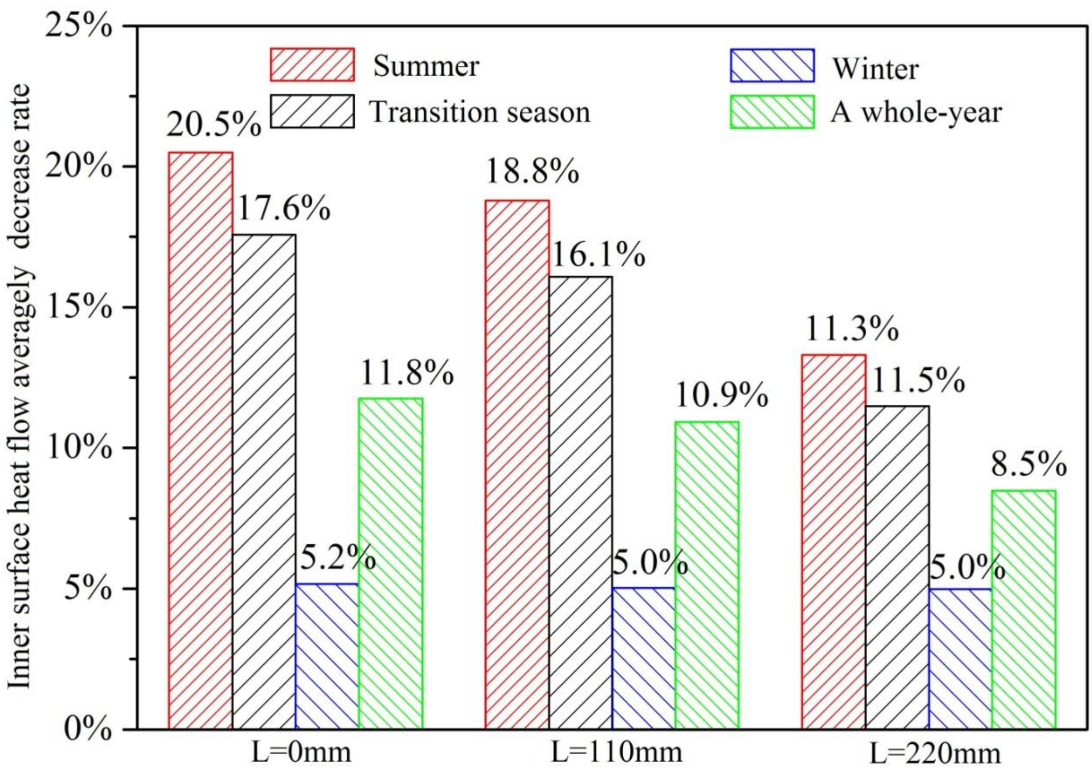

Figure 5-6 Comparison of the average heat flow decrease rate under the different locations of the PCM layer

5.2.3 Analysis on improvement effect of multi-layer wall thermal performance with PCMs under different wall structure

Research on the improvement effect of PCM on multi-layer wall when PCM layer is added to different wall structure is made in this section. And phase change of PCM is just occurred in summer season, the PCM are all located in wall inner side, wall structure is shown in Figure 4-19, and the PCM phase change range is set as Table 4-9.

Figure 5-7 gives the variation situation of multi-layer wall integrated PCM inner surface temperature with time when PCM layer is added to different wall structure in summer; It can be found that in summer when PCM is located in wall inside, because of the influence of PCM exothermal and heat storage capacity, wall structure 1 inner surface temperature wave peak decrease amplitude is largest, decrease rate is up to 83.8%. then is wall structure 2 and wall structure 3, the value is 71.2% and 66.2% separately; the worst effect is for wall structure 4.

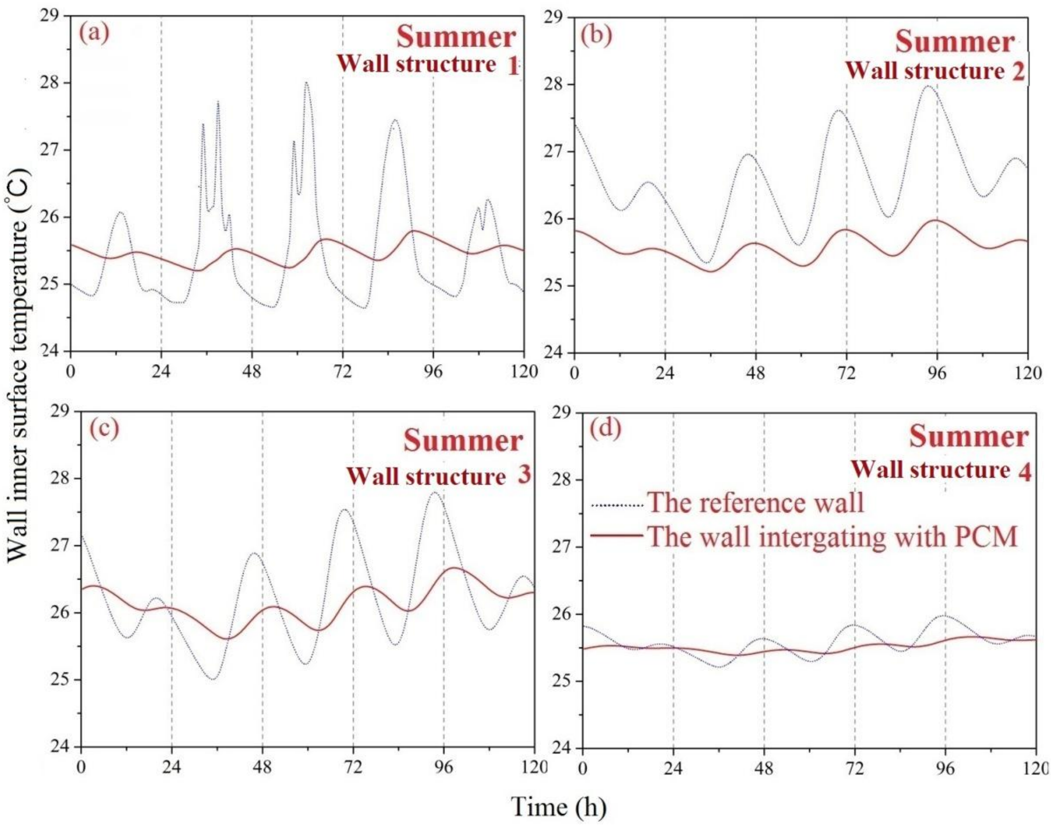

Figure 5-7 Variation of multi-layer wall integrated PCM inner surface temperature with time in summer

Figure 5-8 shows the variation situation of multi-layer wall integrated PCM inner surface temperature with time when PCM layer is added to different wall structure in transition season, wall inner surface temperature has the similar variation rule with that in summer. The inner surface temperature decrease rate in transition seasons is lower than that in summer season especially for Wall structure 2.

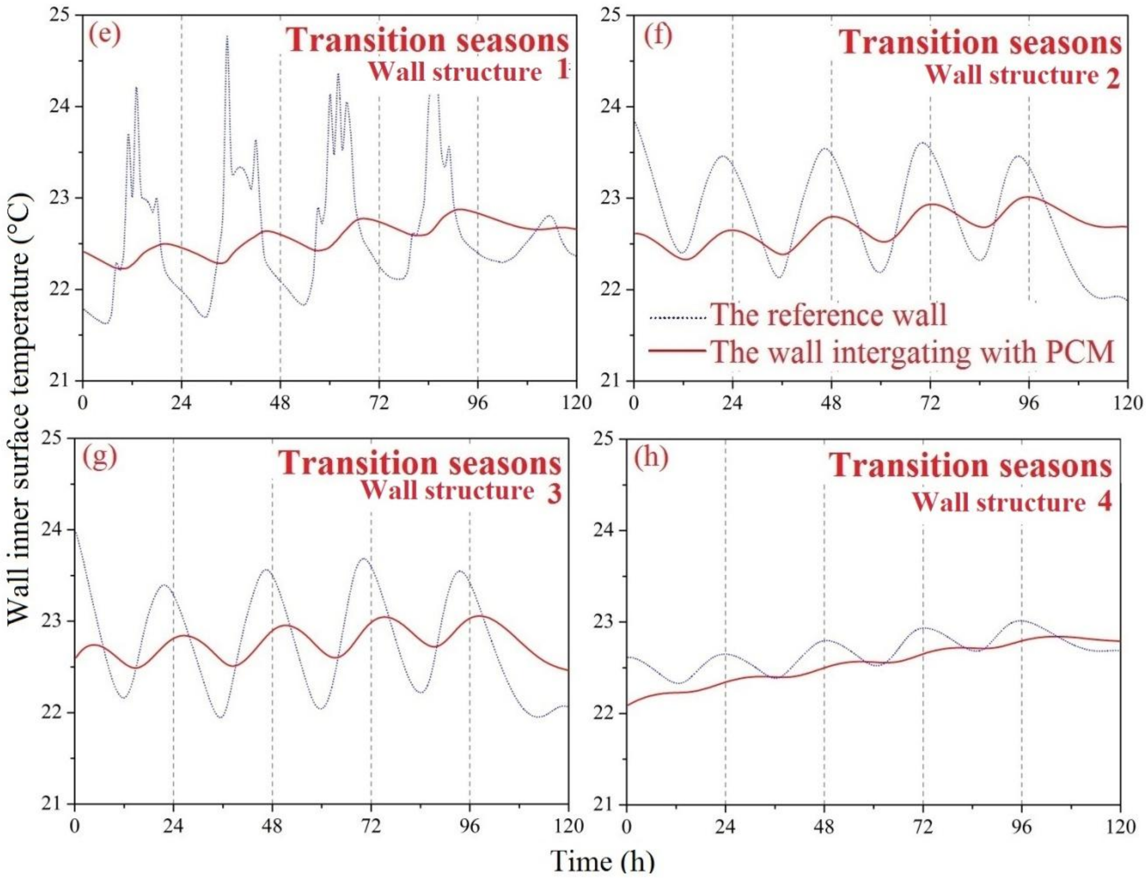

Figure 5-8 variation of multi-layer wall integrated PCM inner surface temperature with time in transition season

In winter, wall integrating with PCM layer inner surface temperature under different wall structure is shown in Figure 5-9. It can be shown that even PCM phase change range does not cover the season, there is no phase change, the increase of wall thickness because of the PCM layer can improve wall thermal performance in a certain extent. And the improvement effect of Wall structure 2 is most obvious because it can be found that the inner surface of wall structure 2 is always higher than that of the reference wall. The inner surface temperature of Wall structure 4 is basically same with the reference wall which means that the PCM layer have no effect for improve indoor temperature. And the improvement effect for Wall structure 2 and Wall structure 3 are also small.

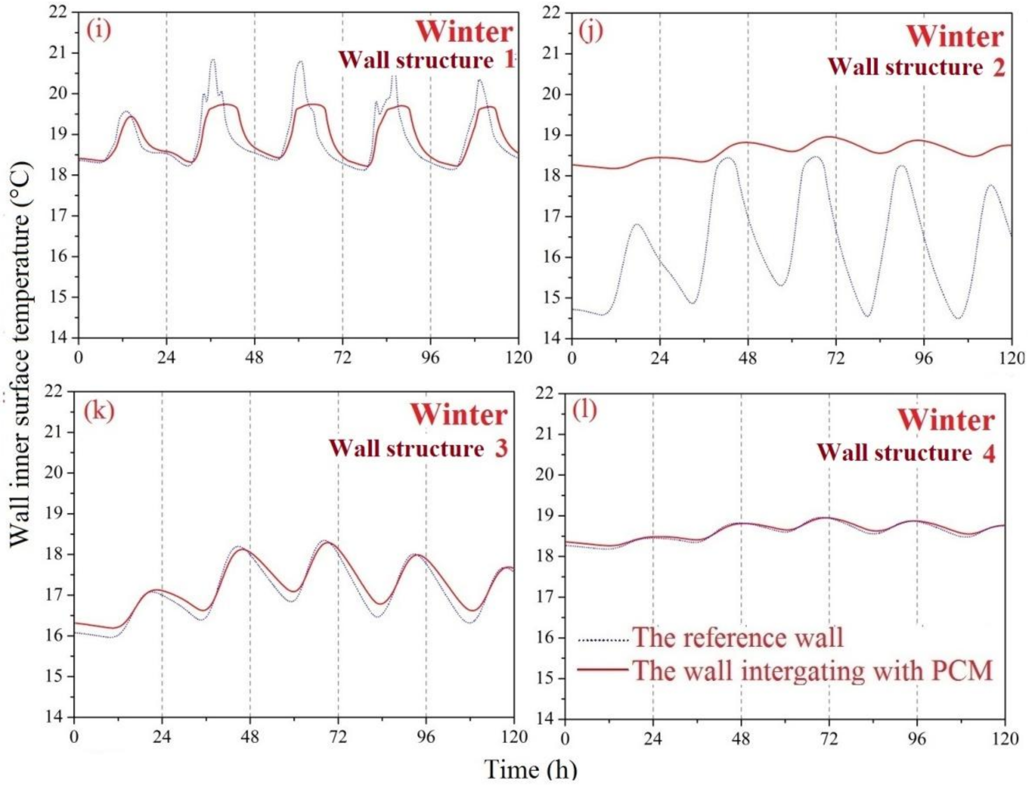

Figure 5-9 variation of multi-layer wall integrated PCM inner surface temperature with time in winter

Through future analysis on wall inner surface temperature fluctuation of different wall structure, for wall without PCM layer, wall structure 1 has the biggest inner surface temperature decay because of its worst wall heat storage capacity; then is wall structure 2, wall structure 3 and wall structure 4. Therefore, to the improvement effect on wall thermal performance, PCM layer has a certain selectivity for different wall structure; the worst thermal inertia of wall structure, the best improvement effect on wall thermal performance of PCM layer. The reason for this phenomenon is that the main way for PCM layer improve wall thermal performance is increase wall thermal inertia, so PCM has a obvious effect for light-weight wall with small thermal inertia. And for walls integrated with PCM layer, the improvement effect for wall structure 1 thermal performance is best.

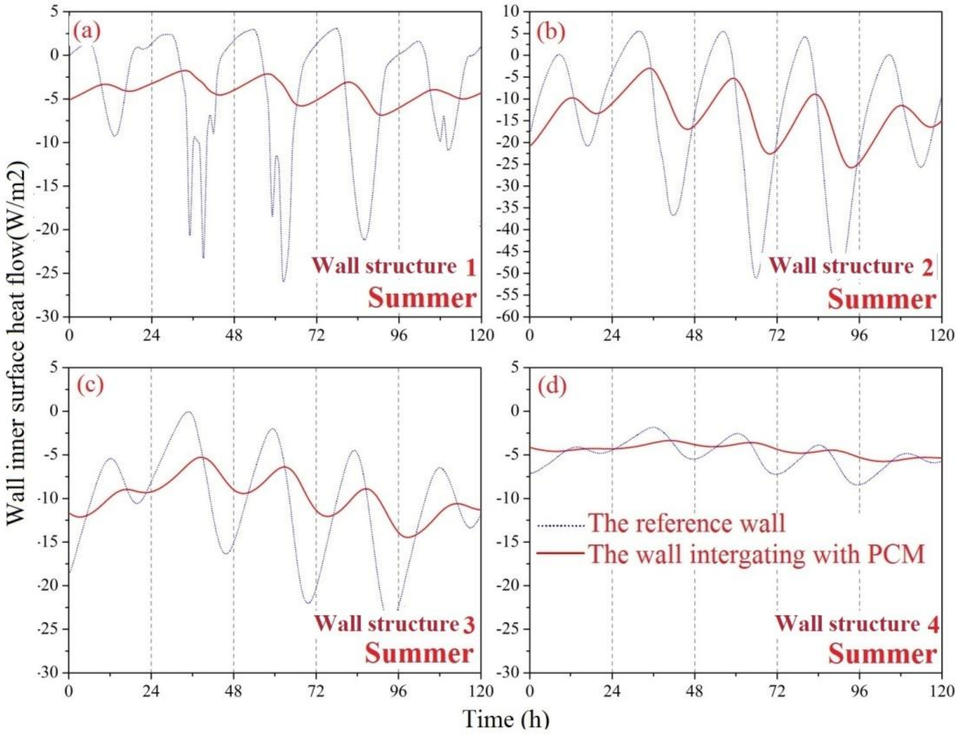

Figure 5-10 variation of multi-layer wall integrated PCM inner surface heat flow with time in summer

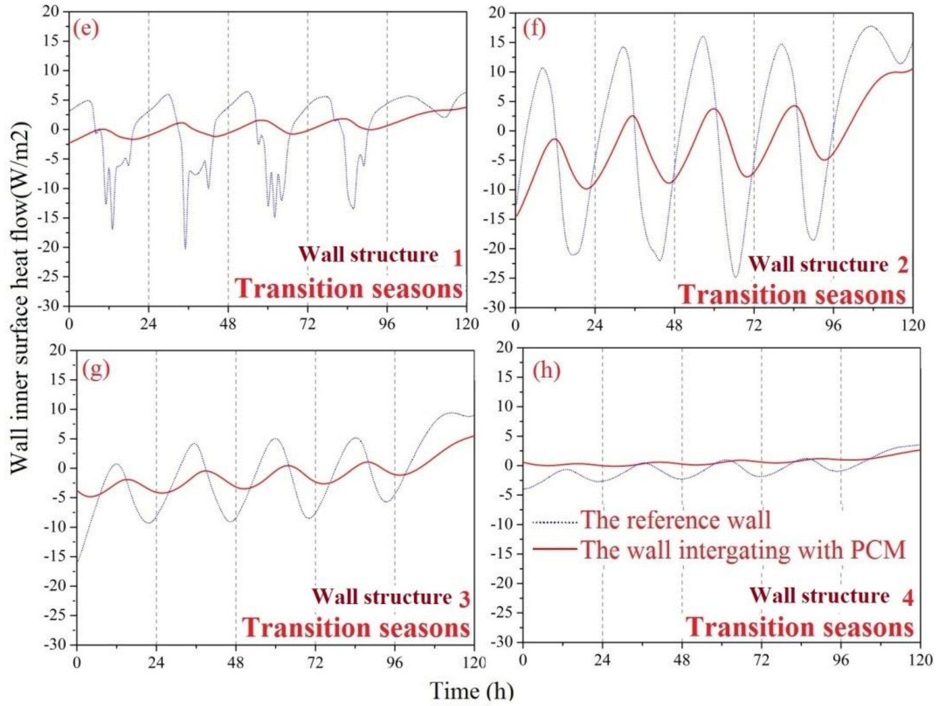

Figure 5-11 variation of multi-layer wall integrated PCM inner surface heat flow with time in transiton seasons

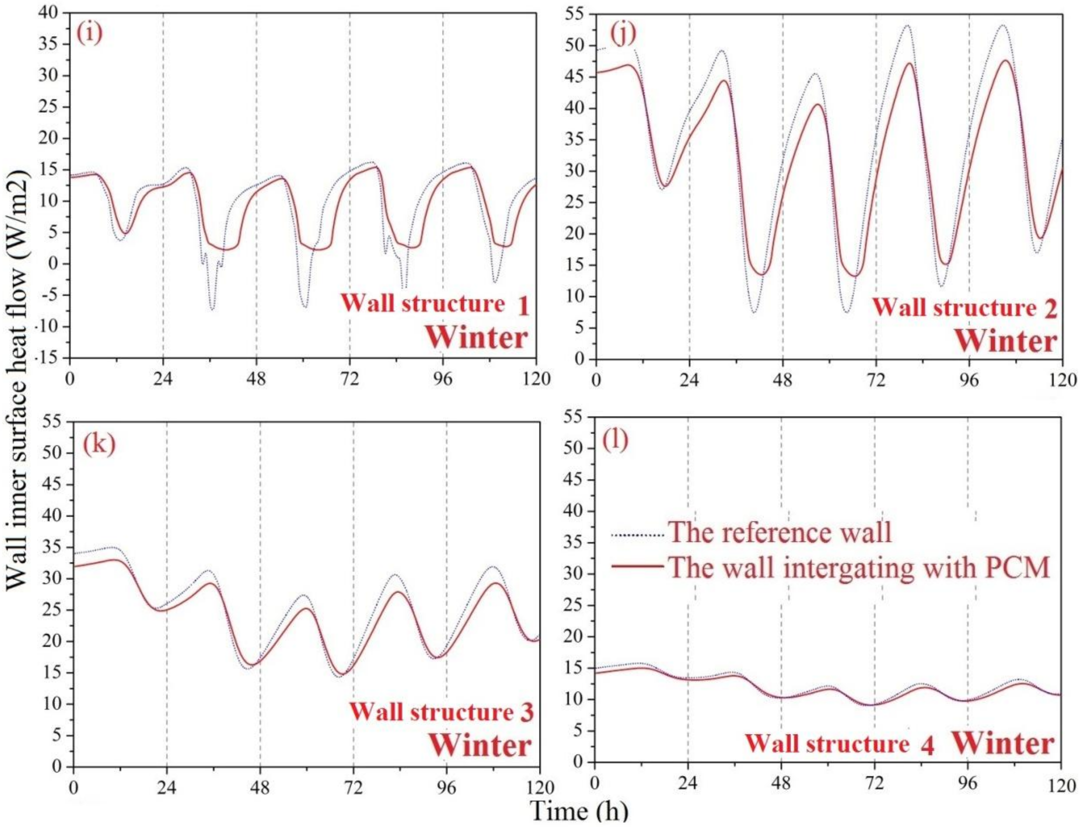

Figure 5-12 variation of multi-layer wall integrated PCM inner surface heat flow with time in winter

Figure 5-10~Figure 5-12 give the variation situation of multi-layer wall integrated PCM inner surface heat flow with time when PCM layer is added to different wall structure in summer. The variation rule is similar with that of inner surface temperature. For walls integrated with PCM layer, in summer and transition season, wall structure 1 inner surface heat flow wave peak decrease amplitude is largest, and the delaying time is longest, then is wall structure 2 and 3; the worst effect is for wall structure 4. However, in winter, compared with summer and transition season, the heat flow wave peak decrease rate is small because of no phase change phenomenon.

Through data processing in Figure 5-10~Figure 5-12, Figure 5-13 shows when phase change range is designed according summer climate condition, wall integrated PCM layer inner surface heat flow decrease rate under different wall structure. For four typical wall, light-weight wall 1 has a obvious wall inner surface heat flow decrease rate, then is Wall 2, Wall 3 and Wall4 in summer season, transition season, a whole- year condition. However, in winter, the largest decrease proportion is for Wall2, then is Wall 1, Wall 3 and Wall4 because in winter the PCM layer is just increasing the thickness of the wall. In addition, the decrease proportion in summer is largest, and in winter it is smallest. So PCM has the best effect of energy saving for light-weight wall.

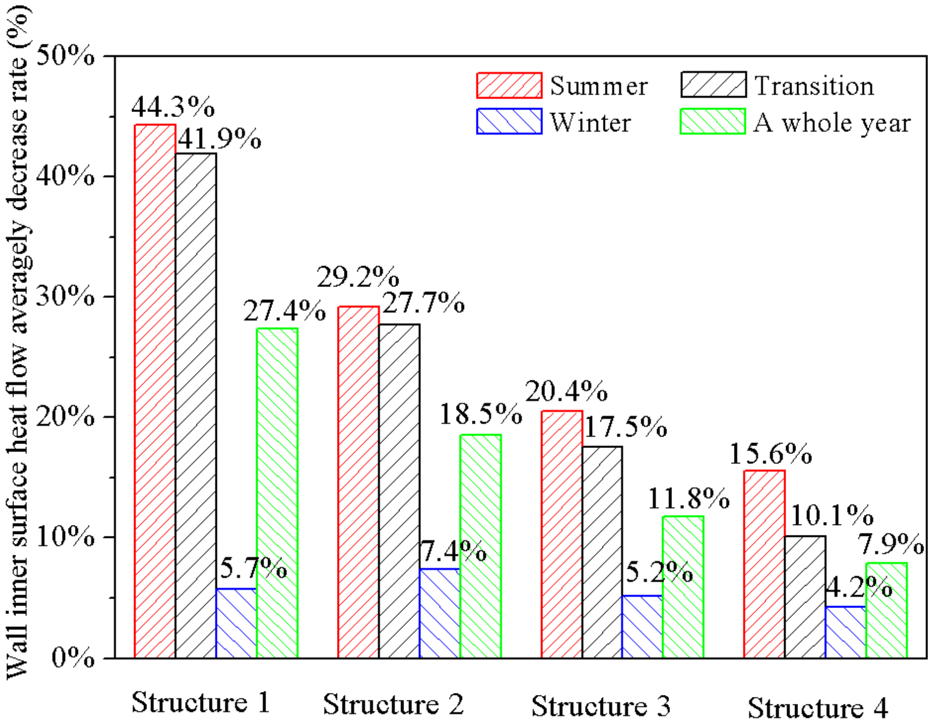

Figure 5-13 Comparison of the average heat flow decrease proportion under the different wall structure

5.3 Research on improvement of walls thermal performance with PCMs layer under intermittent running mode of air conditioning

So far, improving walls insulation property[11-14], increasing energy efficiency of equipments[15-18], optimizing building type[19-21] and energy saving technologies[22-26] are main buildings energy conservation measures. However, building energy consumption is always keeping high and have the phenomenon “energy-efficient buildings are not efficient”. The reason may be air conditioning running model are not reasonable. Most “energy-efficient buildings” runs at a high comfort, full space and continuous operation. However, because indoor environment regulated demand is diversified, intermittent running air-condition is more energy-efficient; at the same time meeting the demand of comfort. And air-conditioning intermittent running has big influence on building energy saving. At the same time climate, envelop structure all has a certain effect on building energy consumption. Liu Y F divided intermittent heating into long intermittent cycle (stop time: more than 1 month) and short intermittent cycle (just stop heating at night). At the base of outdoor calculation temperature, the heating design load can lower 9% and 15% at maximum for long cycle and short cycle[27]. Xu B P made analysis on intermittent heating energy consumption of office building in Beijing. Heating equipments running during 8:00~18:00. Indoor temperature is set up as 18 ^{o}C. Results shows that: the energy saving ration of general building is 1%~5% higher than energy-efficient buildings when air condition is intermittent running. In the early cold period the energy-efficient ratio is 3%~7% higher than that of middle cold period[28]. Ran C Y found a teaching building in Changchun can save 11.7% energy when air conditioning heating is intermittent running than that of continue running[29]. Li R made experiment and found in office air conditioning heating intermittent running can save 40% energy consumption[30]. Wang H F found hat the increase time of air conditioning stop lead to the increase of load and energy saving ratio, the load increase ration is 15.2%~91.8%, energy saving ratio is 4.5%~14.4%[31]. Xie Z L make research on residential building energy saving consumption when air-conditioning is intermittent running in Wen Zhou using the software IES-VE. Results shows heating energy consumption can heating consumption can reduce by 33.5% cooling consumption can reduce by 20.4%, the total air-conditioning energy consumption can reduce by 50.5%[32]. Xu found that stopping air-conditioning at night (8:00-09:00) can reduce air-conditioning energy consumption by 21.7%, at afternoon (15:30-16:30) air-conditioning energy consumption can be reduced by 6.1%[33]. Chao and Zaheer-uddin make comparison analysis on two intermittent running model for panel radiation heating system. Results shows that energy consumption using the preset control mode according outdoor climate condition can save 10%~20% than the traditional on-off mode or simple PI mode[34]. Kim also make research on relationship on energy saving and different intermittent heating mode. Compared with continues heating, preset intermittent control energy saving ratio is

101% and the energy saving ratio of simple on-off mode is 53.1%[35]. Budaiwi and Abdou make research on energy conservation ratio when air conditioning is intermittent and compartment running in a mosque. There is higher heating load and member fluctuation during worship time. Results shows that air-conditioning energy consumption can lower 23% when air-conditioning is running intermittent; when it is running separately in rooms, the energy consumption can reduce by 30%[36]. Xu J F make the influence of outer-insulating composite wall, inner-insulating composite wall and self-insulating composite wall on energy saving ratio of intermittent heating. Even though the heat transfer conductivity coefficient is same ,the energy saving ratio is different significantly. The energy saving ratio of inner-insulating composite is 19.1% ~33.3% higher than that of self-insulation walls[37]. However, for the energy consumption saving ratio of air conditioning intermittent running, different people have different opinions. Bardan make test on a residential building when the air conditioning continues running and intermittent running. Results shows that when air-conditioning keep running for more than 14h, continues running is more economic and is the time is less than 14h, intermittent running is more economic[38]. Zhang X J found that when air conditioning pause for 2h in summer, energy consumption will reduce by 10%, however, when it pause for 2h in winter, energy consumption will increase by 16%[39].Above research shows that intermittent running mode has great influence on air-conditioning and heating energy consumption

5.3.1 Research object and intermittent running model of air conditioning

This section make research on improvement effect on thermal performance of walls integrated with PCMs under the intermittent running of air conditioning in summer. The wall models(Wall structure 1~ Wall structure 3) is shown as Figure 4-19. Among which, Wall structure 1 is board room walls integrated with PCM layer; wall structure 2 is residential building inner wall integrated PCM layer or light-weight building outer wall integrated with PCM layer; Wall structure 3 is residential building outer wall; In addition, according PCM phase change range designed under summer conditions, Table 5-2 shows when PCM is added to wall inner surface and outer surface, the optimum phase change range of PCM Layer obtained according theory calculation methods.

Table 5-2 Optimum phase change range of three typical walls

No	Wall Type	PCM Location	Solidus temperature(℃)	Liquidus temperature(℃)
1	structure 1	Wall outer surface	1.09	40.92
		Wall inner surface	19.60	26.00
2	structure 2	Wall outer surface	4.92	37.45
		Wall inner surface	17.94	29.26
3	structure 3	Wall outer surface	13.06	35.00
		Wall inner surface	18.90	27.30

The base condition is air-conditioning continues running model, and the intermittent running models were got from the questionnaire investigation on net in China Made by Xi Meng. The investigation time is from May 15th and July 15th. The total number of questionnaires is 1701, including 1617 valid questionnaires with a effective rate of 95.06%. Among which, 822 questionnaires are for residential buildings and 795 questionnaires for office buildings. Table 5-3 and Table 5-4 shows the distribution of the questionnaire of residential buildings and office buildings. It can be found that the questionnaire in hot summer and cold winter is most with a proportion above 36%, then is hot summer and warm winter area, above 21%, the proportion for wild area and cold area are separately 19% and 18%.

Table 5-3 Climate area distribution of the questionnaires-----residential buildings(Numbers: 822)

No	Climate area	Number	Proportion
1	Sever cold area	32	5.11%
2	Cold area	146	17.27%
3	Mild area	155	18.98%
4	Hot summer and cold winter area	294	36.01%
5	Hot summer and warm winter area	168	22.63%

Table 5-4 Climate area distribution of the questionnaires-----office buildings(Numbers: 795)

No	Climate area	Number	Proportion
1	Sever cold area	32	4.03%
2	Cold area	146	18.36%
3	Mild area	155	19.5%
4	Hot summer and cold winter area	294	36.98%
5	Hot summer and warm winter area	168	21.13%

Figure 5-14 shows four air-conditioning intermittent running models got from the questionnaire investigation. Figure 5-14 (a) is the common air-conditioning intermittent running models of residential buildings. Intermittent running 1 represents the running model of dinning room and living room, the operating time of air-conditioning is during the breakfast, lunch and dinner with 6 hours. Intermittent running 2 represents the running model of bedroom, the operating time of air-conditioning is rest time at noon and sleep time at night with 4 hours. Figure 5-14(b) is the common air-conditioning intermittent running models of office buildings. Intermittent running 3 means air conditioning keep running 10 hours from 8:00am to 6:00pm during the working time. Compared with intermittent running 3, intermittent running 4 means there is a stop during for air-conditioning during lunch time, 4 hours during the morning and 4 hours during the afternoon. Even the four models have not cover all buildings air-conditionings running models, it is based on the questionnaire investigations, and considering into in-building rate and air conditioning running habits which have covered most air-conditionings running models.

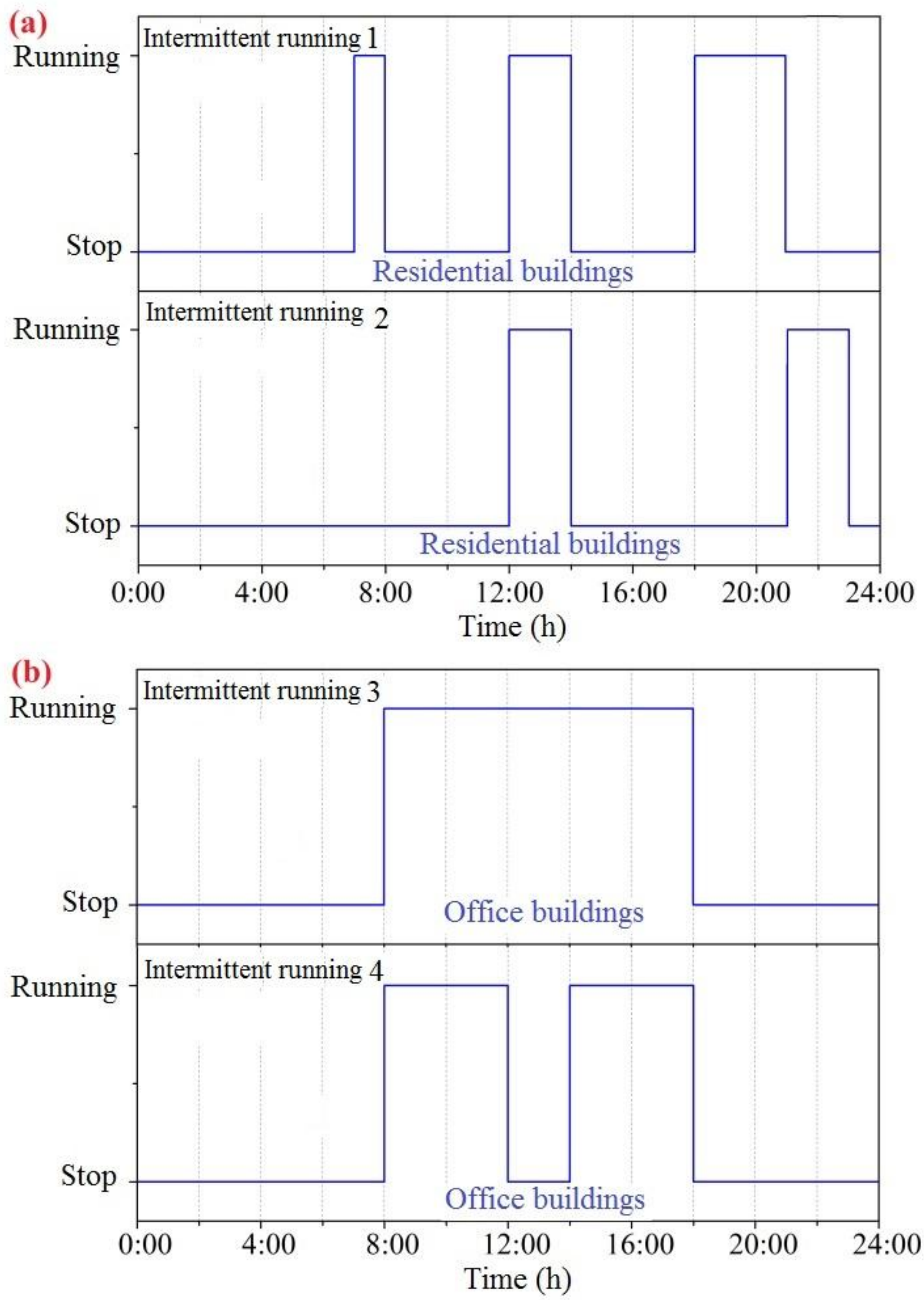

Table 5-14 Air-conditioning intermittent running models (a) residential buildings (b) office buildings

5.3.2 Description of boundary condition

In this chapter, in order to eliminate the influence of daily difference of outdoor thermal environment, outdoor boundary condition of the outdoor air temperature and solar radiation all adopted the experimental measurement in Aug 26th as shown in Figure 5-15.

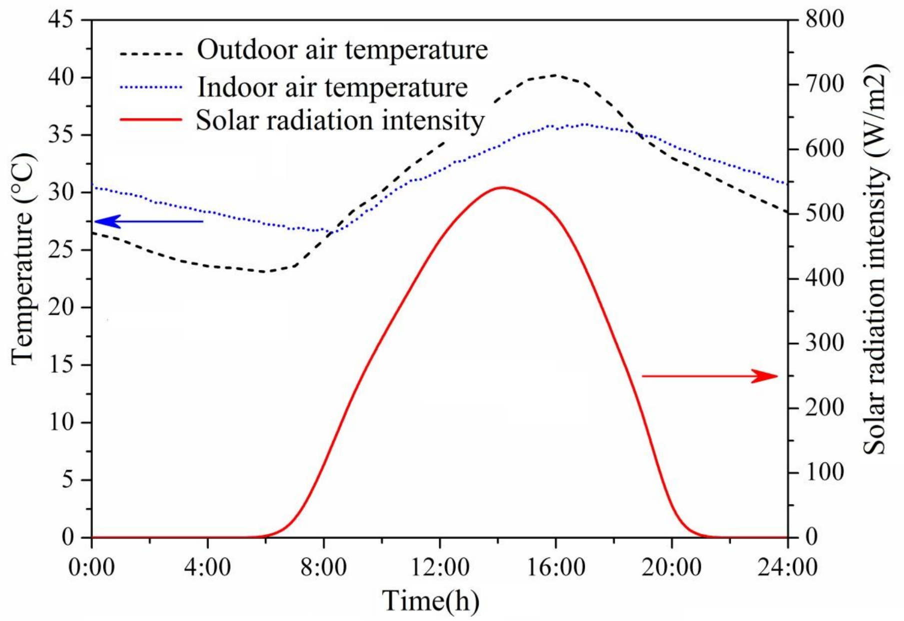

Figure 5-15 Outdoor and indoor temperature and solar radiation intensity of Chengdu in Aug 26th

During the simulation, indoor temperature is obtained according Figure 5-15 under continuing running models. Under intermittent running models, indoor temperature of air-conditioning on-off period is obtained according temperature variation index method proposed by Prof . Long. During on-off period of air-conditioning, indoor temperature of a certain time all meet below equation.

$$T = T_\infty - (T_\infty - T_0)e^{-Bt} \tag{5-2}$$

Where, T_∞ is indoor characteristic temperature during steady state, ℃;

T_0 is indoor initial temperature when the disturbance starts, ℃;

B is the temperature variation index.

According the experimental results in literature, when opening air conditioning, B is 0.0035s-1. T_0 is indoor temperature when open the air-conditioning, T_∞ is indoor stable characteristic temperature, namely indoor air conditioning designing temperature, 25 ℃. When closing air conditioning, B is 0.0035 s-1, T_0 is indoor temperature, $T_\infty$is indoor stable characteristic temperature and we select the value after air conditioning closed 45min. Thereby, at the base of indoor temperature shown in Figure 5-15, combined with the equation (5-2), indoor temperature under four intermittent running models is obtained as shown in Figure 5-16. In addition, during the simulation, indoor and outdoor wall surface connective transfer coefficient are separately 19W/(m2•K) and 8.7W/(m2•K). For the calculation method of multi-layer wall integrated with PCM and verification has been described in Chapter 4. Here will not repeat it.

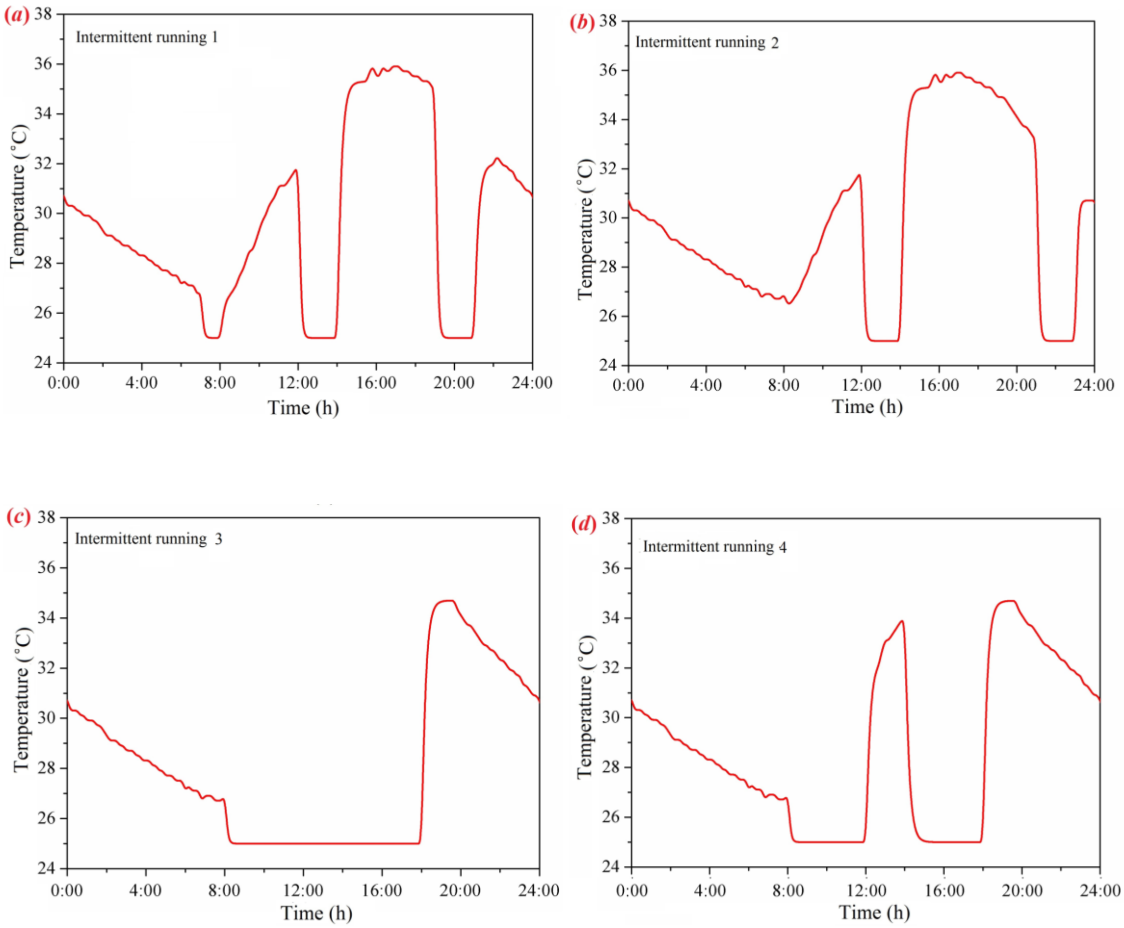

Figure 5-16 Indoor temperature variation with time under four intermittent running model of air conditioning (a) Intermittent running 1 (b) Intermittent running 2 (c) Intermittent running 3 (d) Intermittent running 4

5.3.3 Analysis on thermal response rate of multi-layer wall internal surface integrated with PCM for different type walls

Figure 5-17 shows when designing PCM phase change range according summer climate condition, wall inner surface temperature of wall structure 1 integrated with PCM layer in different complex location with time under five typical air conditioning running models. For “short running cycle period” intermittent running mode 1 and mode 2, wall outer surface integrated with PCM layer temperature response is the quickest, then is wall without PCM layer, the worst is wall inner surface integrated with PCM layer. Which indicates when air-conditioning is running intermittently, PCM layer which is in inner surface cannot improve inner surface thermal response rate, oppositely decrease the value. The reason is when air-conditioning is running intermittently, wall inner surface integrated with PCM layer has high phase change heat storage capacity, the temperate change rate is low. For wall without PCM layer or integrated PCM layer in outer surface, the inner surface material are all EPS and 1mm colored steel (which can be ignored) with small conductivity coefficient and heat storage capacity, then has quick thermal response rate.

Figure 5-18 shows when opening air-conditioning, wall inner surface integrated with PCM wall inner surface heat flow value is higher obviously than that of other two walls. It is also because of PCM high heat storage capacity. However ,when wall integrated with PCM layer in outer side, heat transferred from outdoor can be concordance better. So when all integrates with PCM in outer surface, its heat flow value is smallest. The rule of inner surface temperature and heat flow response rate of intermittent running 1 and intermittent running 2 is consistent.

For intermittent running 3 with “long running cycle”, the most quickest response rate is still wall integrated with PCM in outer surface, than is wall without PCM layer, the worst is wall integrated wall in inner surface. However, compared with intermittent running 1 and intermittent running 2, in this running model , the difference of three typical wall thermal response rate has brought down obviously. The reason is that when opening air conditioning at 8:00 am, the temperature of whole wall is low, so it can arrive saturation statue with small cool storage capacity. From Figure 5-18, it can also been got the heat flow value of wall inner surface is low when opening air-conditioning.

For intermittent running mode 4 with “long running cycle”, the variation rule of temperature and heat flow is same with that in intermittent running mode 3 during period 8:00-12:00 am. Because of high heat storage capacity of PCM, the cool stored during the former air-conditioning running period 8:00-12:00 am is completely release during noon (12:00-14:00) . Therefore, in 14:00, the temperature of wall inner surface integrated with PCM in inside is lowest. And even though, during air-conditioning running period(14:00-18:00), temperature of wall integrated with PCM in inner surface is still higher than other two type wall even low wall thermal response rate. From the heat flow variation rule in Figure5-18 it can also be found that inner surface heat flow value of wall integrated with PCM in inside surface is higher obviously than that of other two type wall.

It can be found that when wall integrated PCM layer in wall inner surface for air-conditioning continue running model, compared with wall without PCM layer, temperature and heat flow amplitude can lower 46%; and when wall integrated PCM layer in outer surface, compared with without PCM layer, temperature and heat flow amplitude can lower 18%. It indicate that for light-weight wall 1, PCM layer at wall inner surface is superior to outer surface.

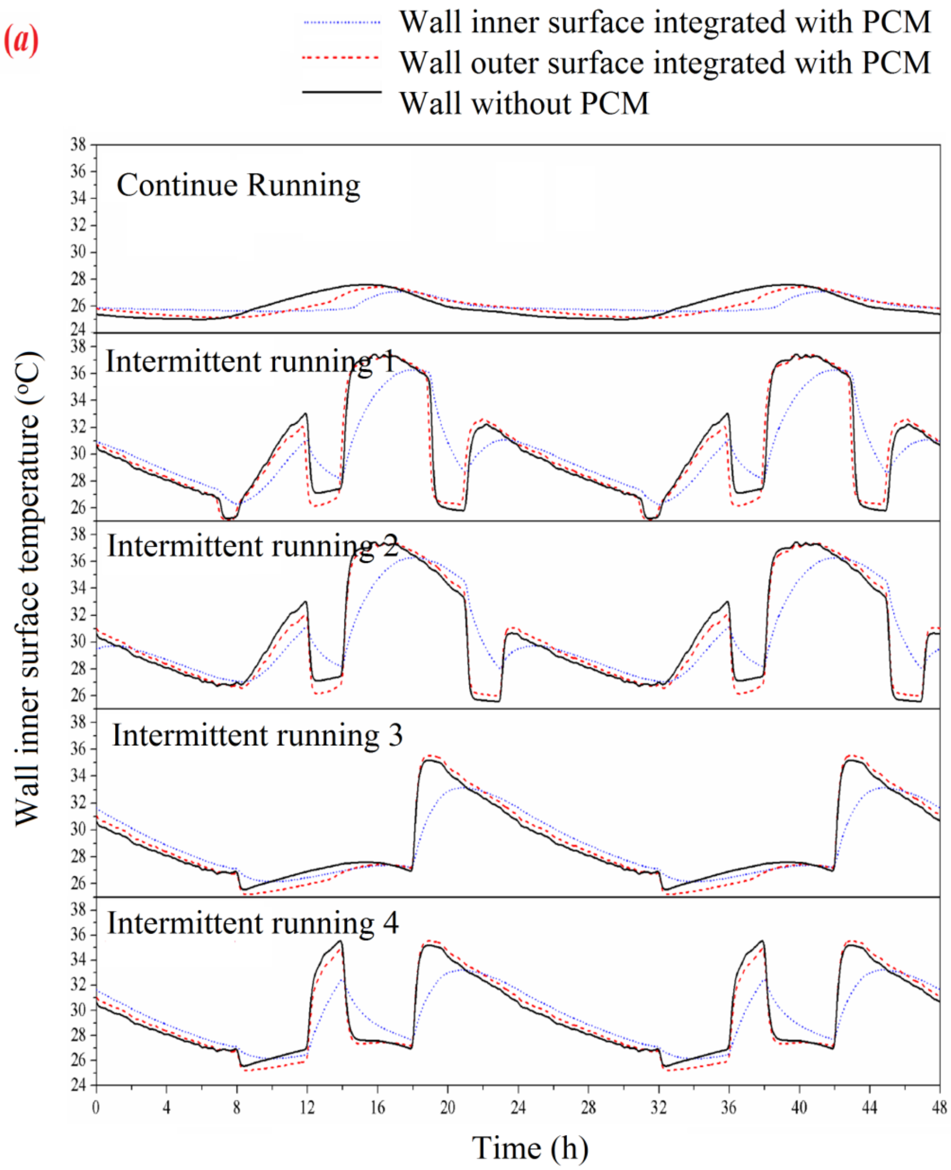

Figure 5-17 Wall structure 1 inner surface temperature variation with time when PCM phase change range is designed according summer climate condition under five typical running models

(*b*)

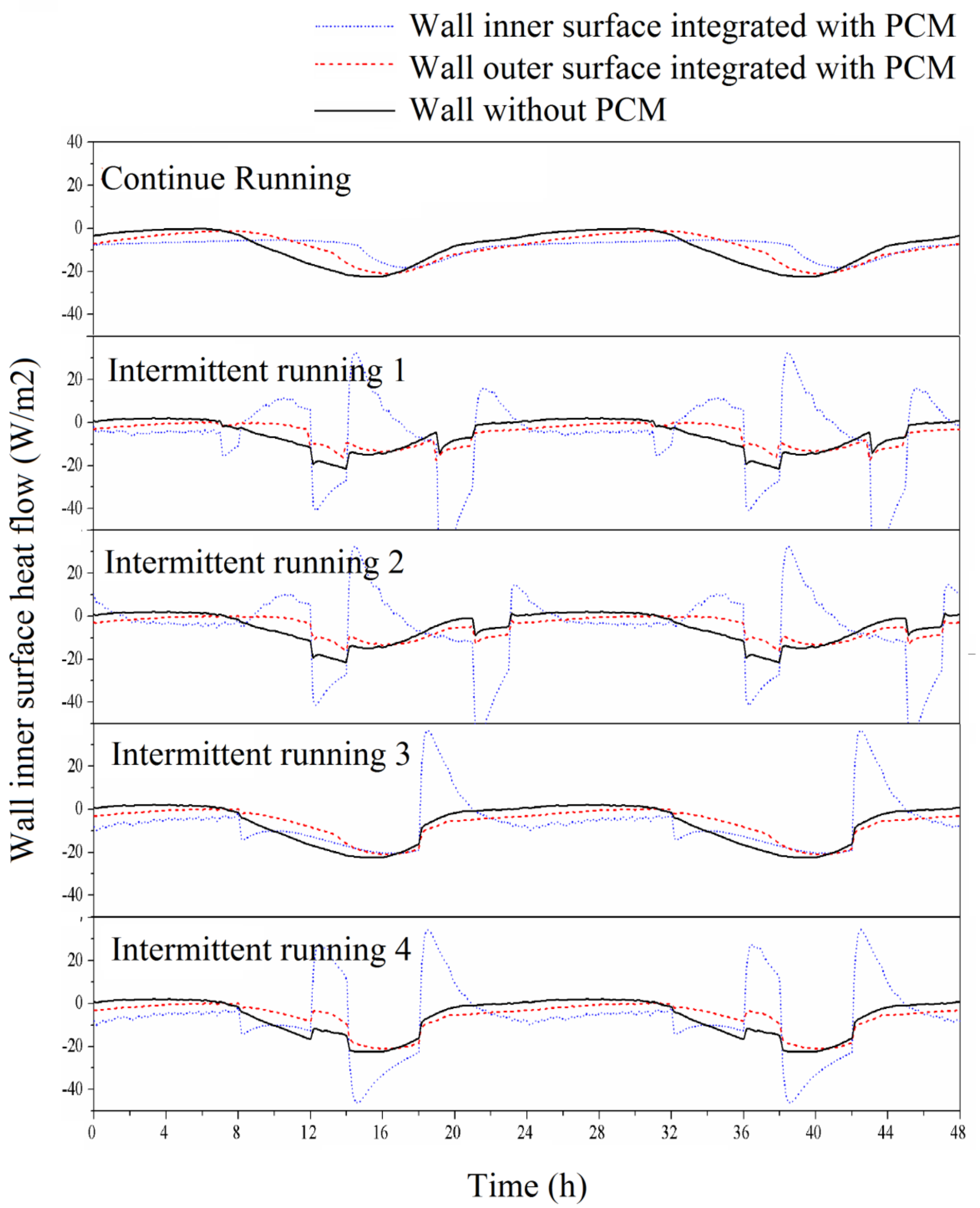

Figure 5-18 Wall structure 1 inner surface heat flow variation with time when PCM phase change range is designed according summer climate condition under five typical running models

Figure 5-19 and Figure 5-20 shows the variation situation of Wall structure 2 inner surface temperature (Figure 5-19) and heat flow (Figure 5-20) when it is integrated with PCM in different composite ways and without PCM layer under five typical running conditions. when designing PCM phase change range according summer climate condition. For air conditioning continue running mode, when PCM is integrated in wall inner surface, compared with wall without PCM, wall inner surface temperature and heat flow amplitude all reduce 56%; when PCM is integrated in outer surface, compared with wall without PCM, wall inner surface temperature and heat flow amplitude all reduce 23%. Above analysis indicates for light weight wall structure 2, PCM in wall inner surface is superior obviously than that of outer surface.

For “short running cycle period” intermittent running model 1 and 2, wall structure 2 with PCM in outside and inside has basically consistent inner surface temperature and heat flow response rate. But during different air-conditioning running period, there are a obvious difference between different walls inner surface temperature and heat flow. Such as during running period 7:00~8:00 am, the temperature of wall structure 2 without PCM is lowest, and heat flow value is also lowest. However, during running period 12:00~14:00 and 18:00~20:00, temperature and heat flow value of wall structure 2 with PCM layer in its inner surface is lowest.

However, during air-conditioning running period 20:00~23:00, three type wall structure has consistent inner surface temperature and heat flow. The reason is during different running cycle, the stating temperature has a big difference. At 7:00, outdoor temperature is low at night, so wall with worse insulation property has lower wall temperature and higher cool storage capacity. Therefore, during running period 7:00~8:00, wall without PCM layer inner surface temperature is lowest; at 12:00 and 18:00, outdoor temperature is high, the wall inner surface temperature and heat storage capacity of wall with good insulation property is low. So during running period 12:00~14:00 and 18:00~20:00, wall structure 2 integrated PCM layer in inner surface has low inner surface temperature and heat flow value.

For intermittent running mode 3 with “long running cycle”, during preliminary stage 8:00~18:00, because wall without PCM is susceptible to cold air at night, the preliminary temperature is lowest, then is wall integrated with PCM in outer surface, next is wall integrated with PCM in inner surface. In addition, with the increase of outdoor environmental temperature, the advantage of wall without PCM layer low preliminary temperature gradually decreasing, the advantage of wall integrated with PCM is increasing apparent. During the running period of 10:00~14:00, wall integrated with PCM in outer surface has the lowest temperature and heat flow value; however, during the running period of 14:00~18:00, wall integrated with PCM in inner surface has the lowest temperature and heat flow value;

For intermittent running mode 4 with “long running cycle”, during former air-conditioning cycle (8:00-12:00), the variation rule of mode 3 and mode 3 are almost consistent; during the later air conditioning cycle (14:00-18:00), walls integrated with PCM inner surface and outer surface temperature and heat flow are almost consistent.

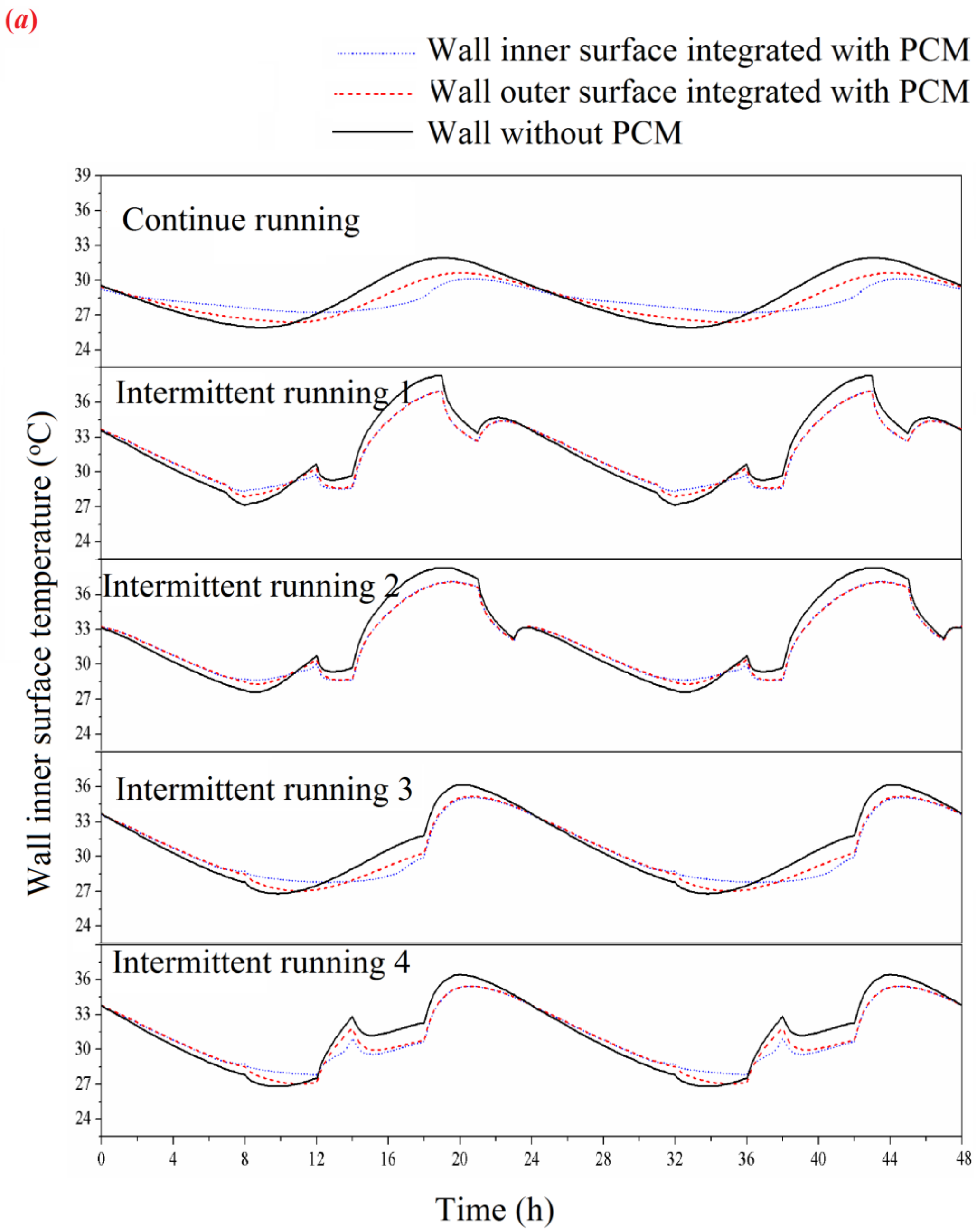

Figure 5-19 Wall structure 2 inner surface temperature variation with time when PCM phase change range is designed according summer climate condition under five typical running models

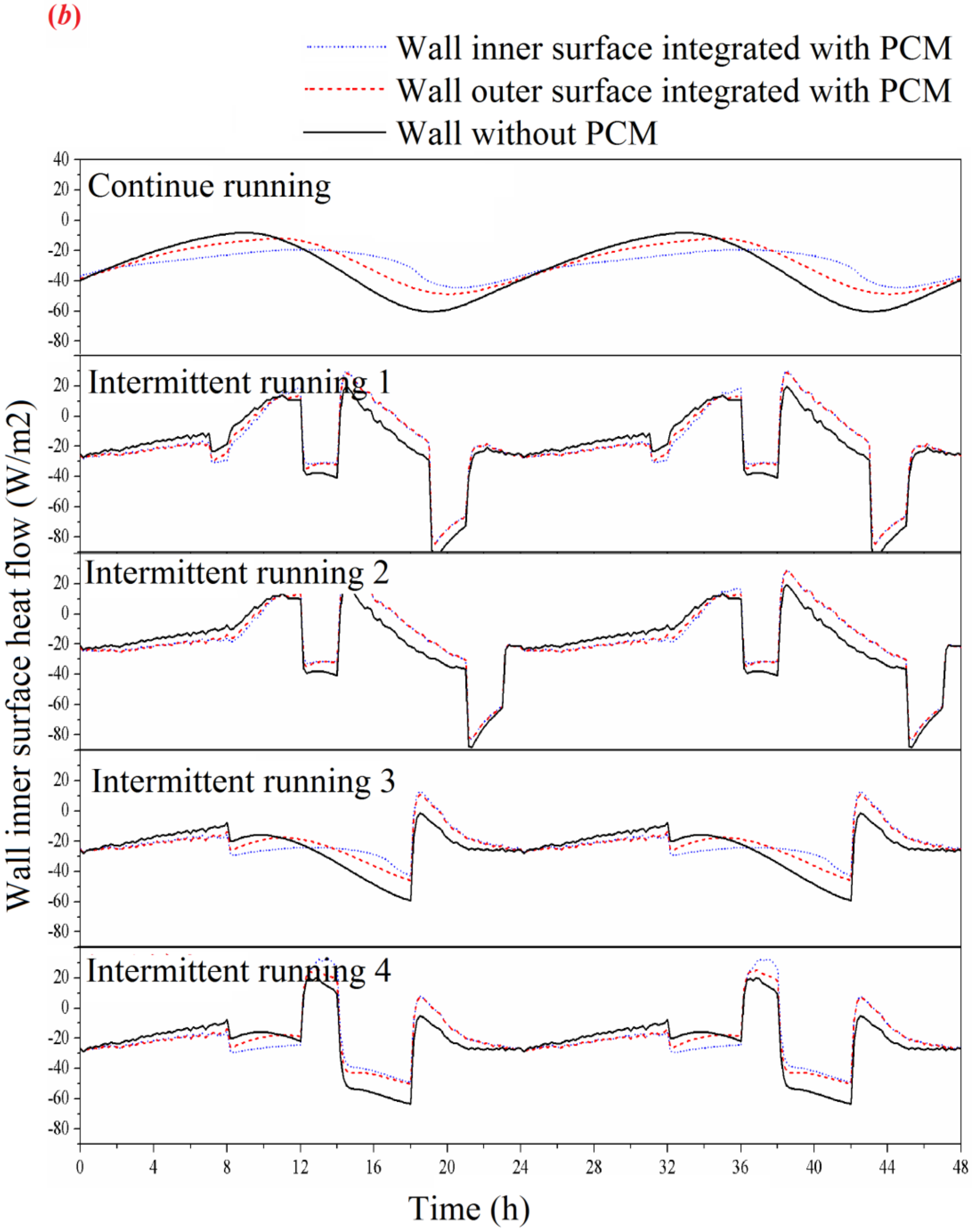

Figure 5-20 Wall structure 2 inner surface heat flow variation with time when PCM phase change range is designed according summer climate condition under five typical running models

In addition, no matter continue running mode or intermittent running mode, the temperature and heat flow variation rule of wall structure 3 in Figure 5-21 and Figure 5-22 and Wall structure 2 in Figure 5-19 and 5-20 is basically consistent. However , the thermal performance of Wall structure 3 is superior to Wall structure 2 apparently, so the influence effect of PCM on Wall structure 3 is lighter than that of Wall structure 2.

Through the comparison of Wall 1 and Wall2-3, it can be found easily, for Wall structure 1, wall integrated with PCM in inner side can weak inner surface thermal response rate. And for Wall structure 2-3, this weakening effect is not apparent. The reason is the thermal response rate of PCM itself is very low. And there just 1mm thickness colored steel on Wall structure 1 inner surface which can be ignored, so the property of thermal response rate of PCM is very evident. There is 10 mm thickness plaster layer on inner surface of Wall structure 2-3, the influence of this plaster layer on wall inner surface thermal response rate is more direct, so the low thermal response rate property of PCM is not apparent.

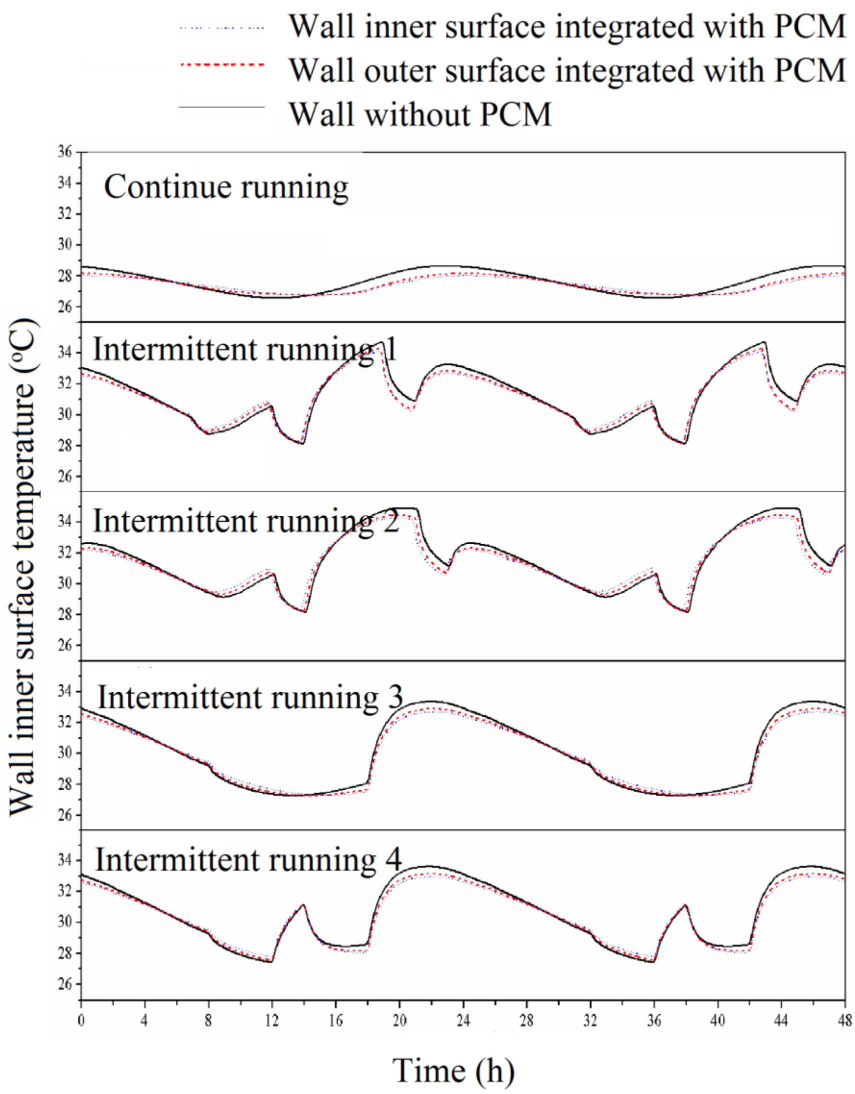

Figure 5-21 Wall structure 3 inner surface temperature variation with time when PCM phase change range is designed according summer climate condition under five typical running models

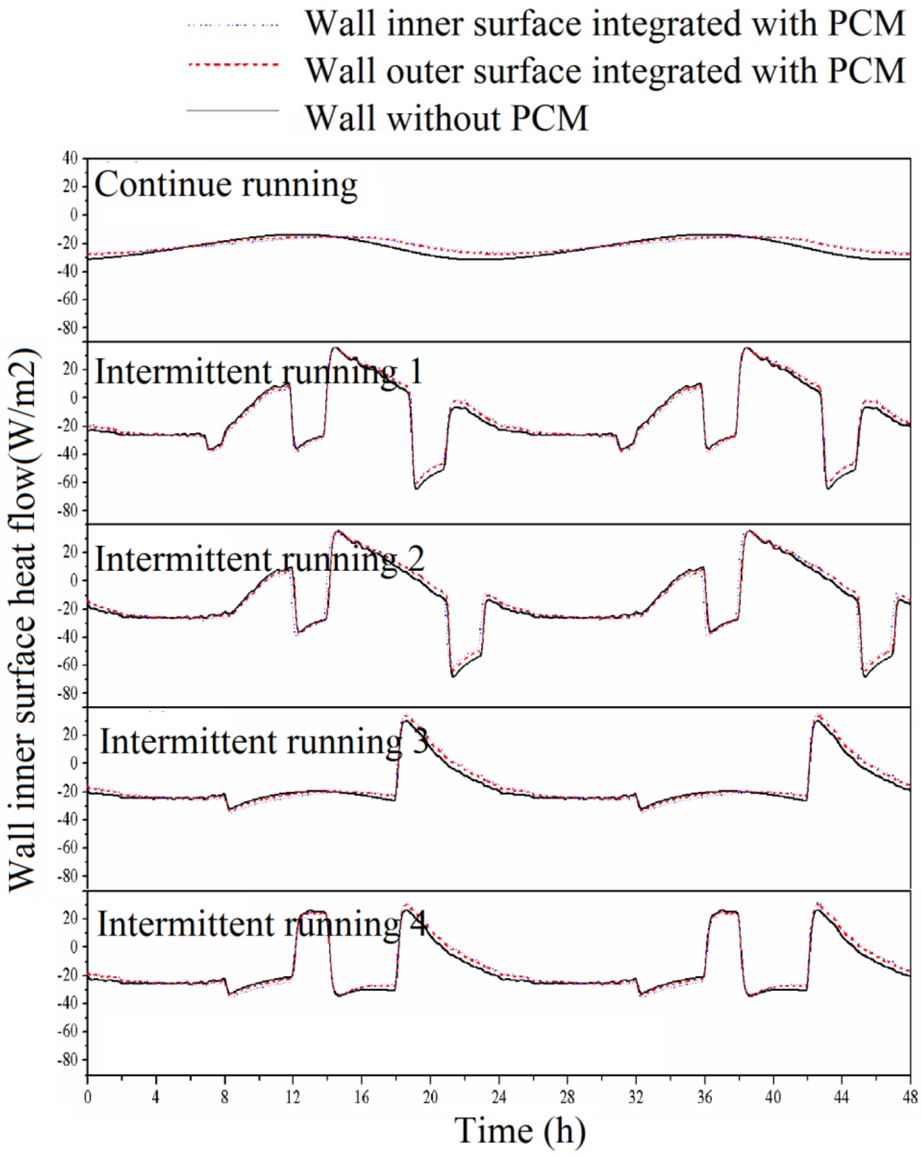

Figure 5-22 Wall structure 3 inner surface heat flow variation with time when PCM phase change range is designed according summer climate condition under five typical running models

5.3.4 Analysis on energy saving ratio of multi-layer wall inner surface integrated with PCM for different type walls

Figure 5-23 shows the wall energy saving effect when air conditioning is intermittent running at the base of air-conditioning continue running. It can be found that for light-weight wall (Wall structure 1), wall inner surface heat flow reduction rate of wall integrated PCM in outer surface is highest, then is that wall without PCM, the last is that of the wall with PCM in inner surface. For intermittent running mode with “short running cycle”, wall inner surface heat flow of wall without PCM and integrated with PCM in outer surface are all higher than that of wall integrated PCM in inner surface. The reason is during air conditioning intermittent running mode with “short running cycle”, wall inner structure has big influence on temperature and heat flow; and for air conditioning intermittent running mode with “long running cycle”, wall comprehensive thermal property has a more evident effect on inner surface heat flow. Wall integrated with PCM in inner surface can improve the energy saving effect; such as air-conditioning running mode 3, at the later stage of air-conditioning running 8 hours, the running rule is similar to air conditioning continue running, so wall integrated PCM in inner surface is superior to that of outer surface.

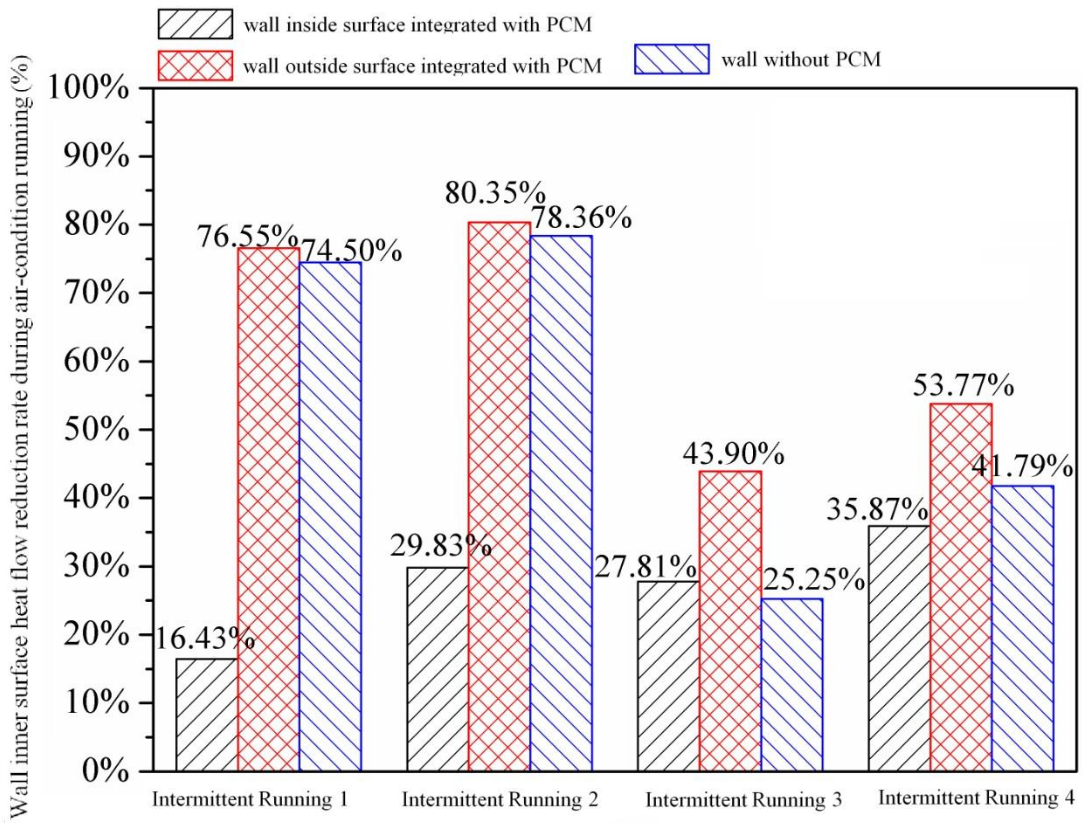

Figure 5-23 Energy saving statistical situation of Wall structure 1 under air-conditioning intermittent running mode at the base of continue running mode.

For middle-weight structure Wall structure 2 (5-24)and heavy-weight structure Wall structure 3(5-25), compared with continue running mode, the average heat flow reduction rate are 64% and 60% under four intermittent running mode, and the difference between these four mode are small.

Compare intermittent running mode 3 and mode 4, it can be found that the average inner surface mode heat flow of wall 1 under mode 3 is 10% higher than that under mode 4. And average inner surface heat flow of wall 2 and wall3 under mode 3 is 2~3% than that under mode 3. It indicates that for light-weight structure wall, a short break during air conditioning long running has an evident influence on wall energy saving effect. For middle-weight structure wall and heavy-weight structure wall, the influence is not apparent.

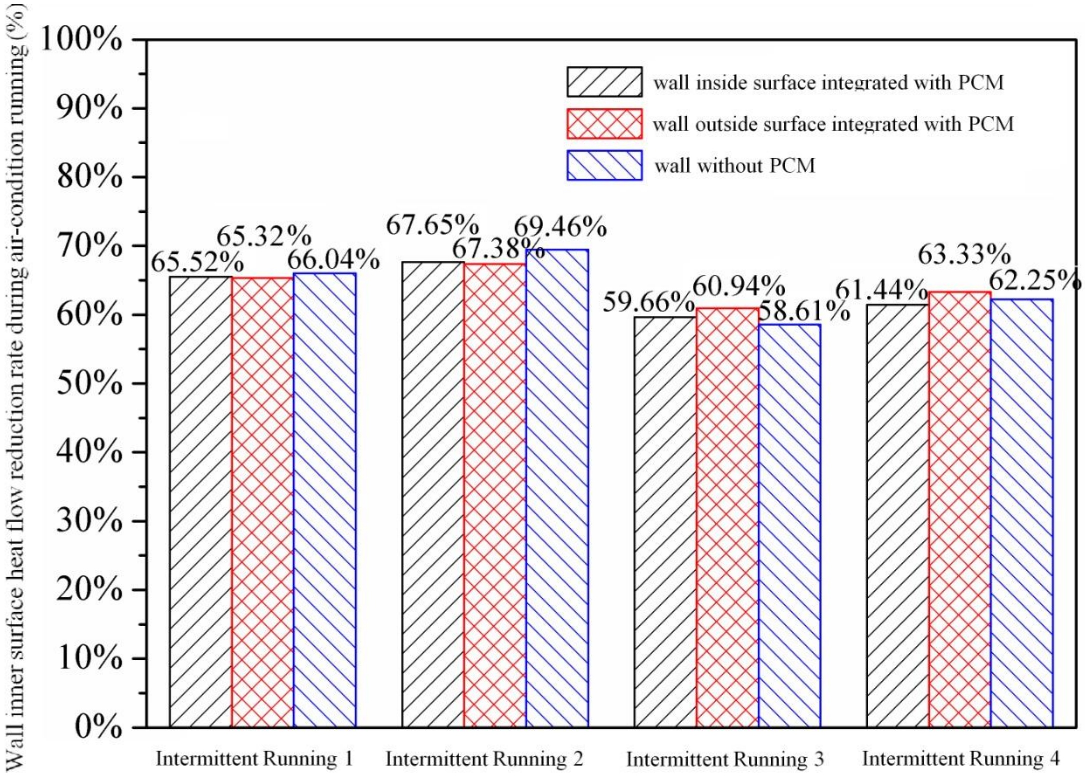

Figure 5-24 Energy saving statistical situation of Wall 2 under air-conditioning intermittent running mode at the base of continue running mode.

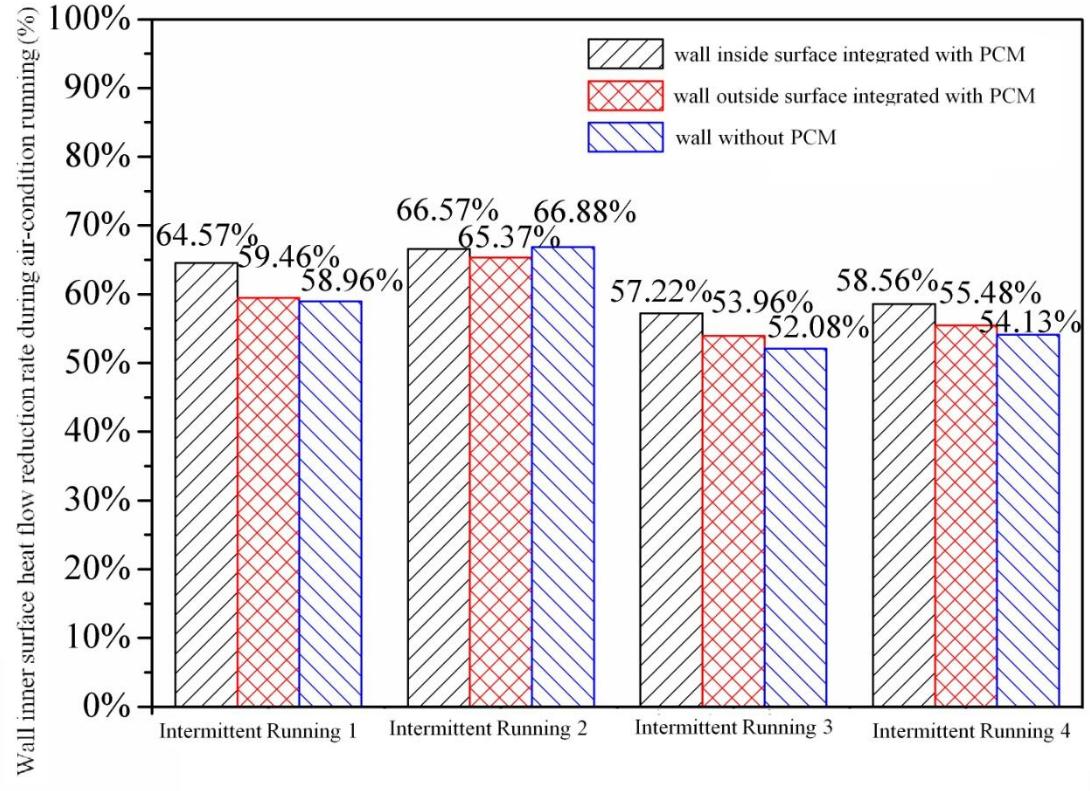

Figure 5-25 Energy saving statistical situation of Wall structure 3 under air-conditioning intermittent running mode at the base of continue running mode.

Figure 5-26~5-28 shows the energy saving effect statistical situation of wall integrated PCM layer at the base of wall without PCM layer. It can be found that for light-weight structure wall(Wall 1), when air conditioning is running continually, wall inner surface heat flow reduction rate are separately 2.79% and 2.82% for PCM is separately on wall inside and outside; and when air conditioning is running at intermittent running mode, the wall thermal effect difference is big for PCM on wall inside and outside. For intermittent running mode 1 and mode 2, when PCM is added on wall inside, wall inner surface heat flow reduction is above -200%. It shows that adding PCM layer on wall inner surface not only cannot reduce energy consumption, but also increase air-conditioning load caused by envelops. When PCM is added to wall outside, inner surface heat flow reduction rate are separately 10.6% and 11.75%; for intermittent running mode3, no matter PCM is added to wall inside or outside, inner surface heat flow are all reduced, however, the reduction value of wall integrated wall in outer surface is lower apparently than that of inner surface. For air-conditioning intermittent running mode 4, when PCM is added to wall inside, it can also be found that the inner surface heat flow reduction rate is negative value.

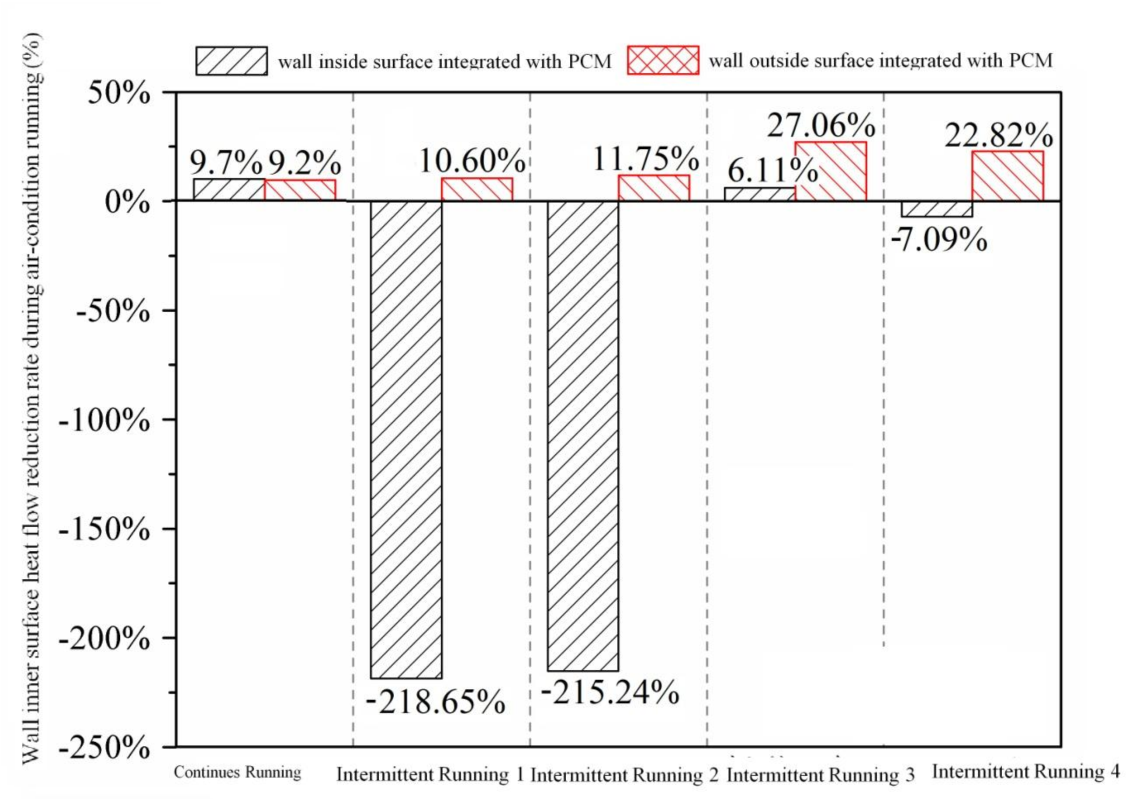

Figure 5-26 Energy saving statistical situation of Wall structure 1 under different running mode at the base of wall without PCM layer

For middle- weight structure wall (Wall structure 2) and heavy-weight structure wall (Wall structure 3), compared with wall without PCM, PCM can both reduce wall inner surface heat flow. However, the reduction values have big difference. For intermittent running mode with “short running cycle”, the energy saving rate of two type wall integrated with wall are both lower than that of walls under air conditioning continue running mode, and wall integrated PCM in inside is superior than that of outside; in other aspect, during the same air conditioning situation, energy saving rate of Wall structure 2 is better than that of Wall structure 3.

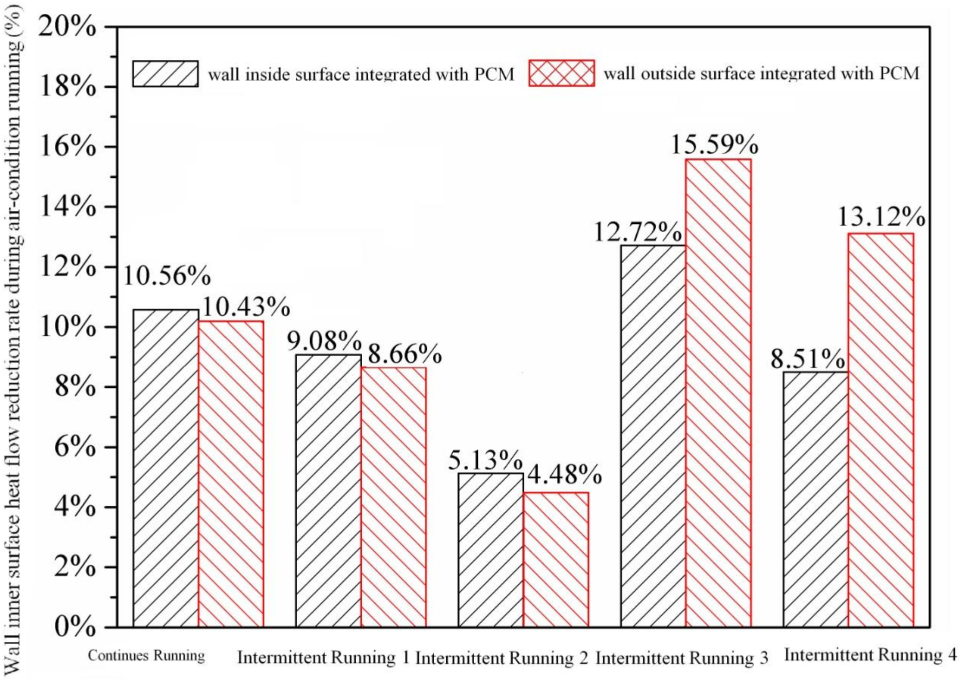

Figure 5-27 Energy saving statistical situation of Wall structure 2 under different running mode at the base of wall without PCM layer

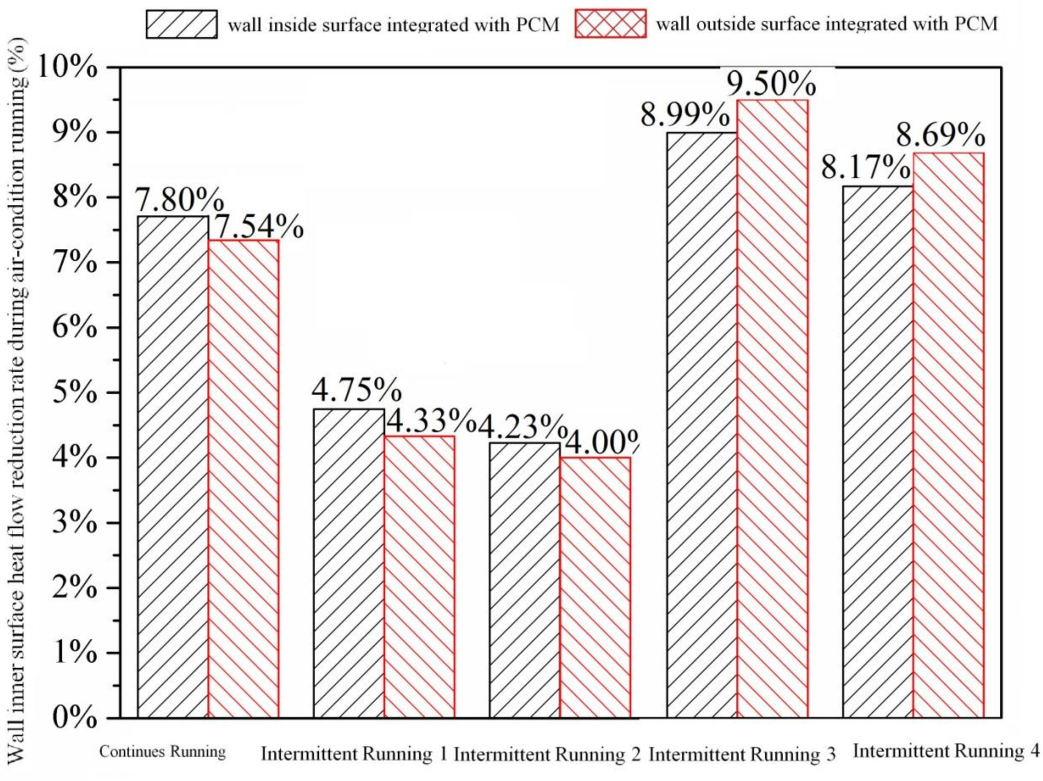

Figure 5-28 Energy saving statistical situation of Wall structure 3 under different running mode at the base of of wall without PCM layer

Figure 5-28 shows the energy saving comparison of three wall structure s when PCM is in wall inner surface based on that wall without PCM layer. It can be found that for continues running mode, three wall structure all have wall inner surface heat flow reduction compared with wall without PCM layer. For the intermittent running mode with "short running cycle" (intermittent running 1, 2 and 4), PCM in wall inner surface not only cannot improve the wall inner surface heat flow reduction rate, but also have harmful effect. Intermittent running 3 have keep running for 8 hours, so it have the similar result with continue running mode.

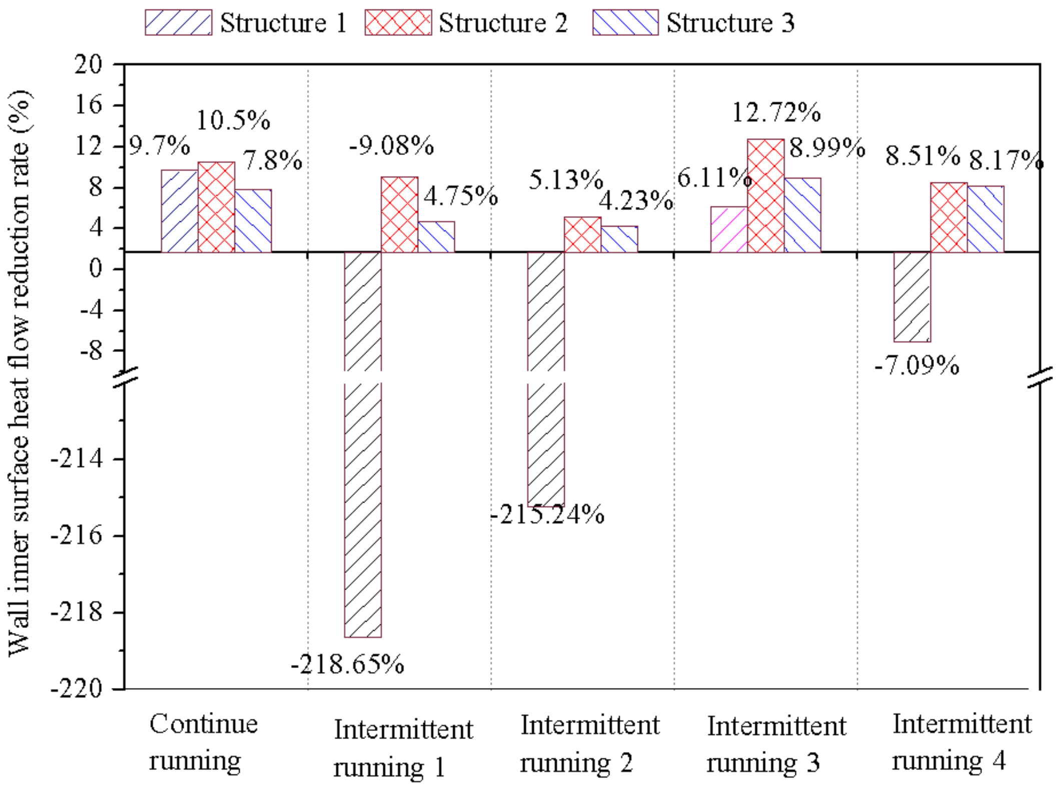

Figure 5-29 Comparison of wall inner surface heat flow heat flow reduction for three different wall structure when PCM layer is in wall inner surface based on wall without PCM

Figure 5-30 shows the energy saving comparison of three wall structure s when PCM is in wall outer surface based on that wall without PCM layer. It can be found compared with walls without PCM layer, PCM in wall outer surface all can improve wall energy efficiency. However, for the intermittent running modes, ultrathin wall (structure 1) have the biggest inner surface heat flow reduction rate and the value for structure 3 is smallest.

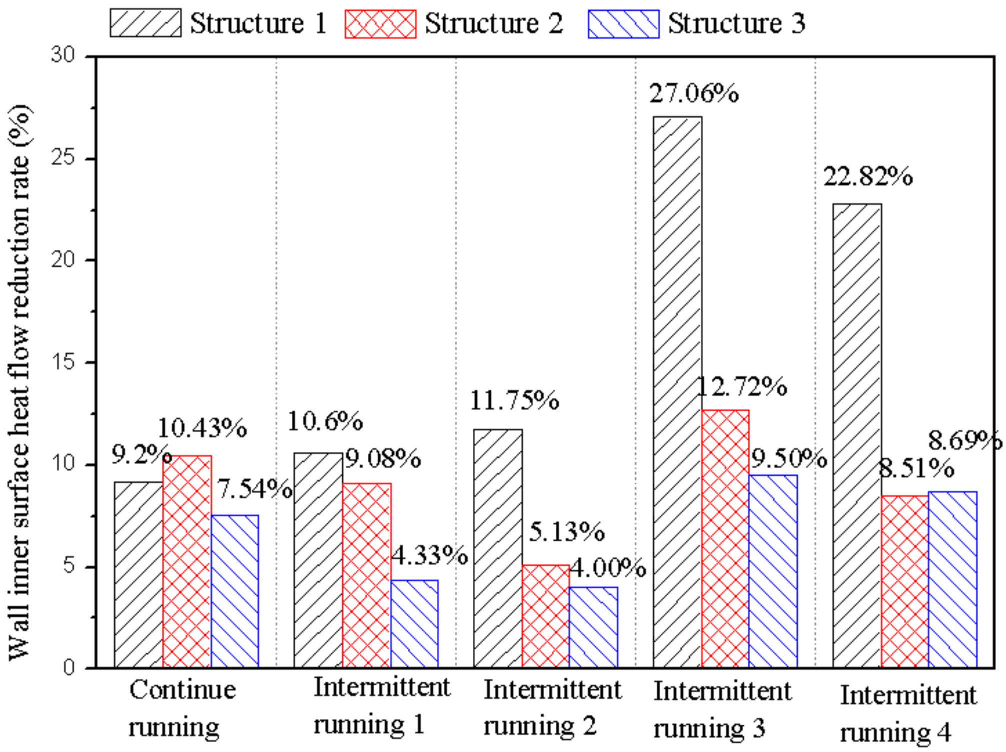

Figure 5-30 Comparison of wall inner surface heat flow heat flow reduction for three different wall structure when PCM layer is in wall outer surface based on wall without PCM

5.4 Summary

This chapter make quantitative analysis on improvement effect of PCMs on multi-layer walls under air-conditioning continue running and intermittent running from wall inner surface temperature and heat flow wave reduction rate and delayed time. And conclusion can be obtained as bellows:

(1) When the air conditioning is continues running, under the different phase change design case, the improvement effect is best when the air condition running period covers the phase change range design case. Such as in summer, when the phase change range is designed according summer climate condition, the reduction rate of multi-layer wall surface temperature and heat flow is largest and the wave peak value delayed time is longest. In addition, even when designing PCM phase change range, some season is not included, wall inner surface also has a heat flow decrease rate because the PCM layer can add the wall thickness.

(2) When the air conditioning is continues running, for the different location of PCM layer, the variation of wall inner surface temperature and heat flow is same and the closer of PCM layer to inner surface, the delayed time and wave peak decrease rate is bigger. For example, in summer, when L is 0 mm, the decrease rate is 20.5% ; when L is 220mm, the decrease is 11.3%

(3)When the air conditioning is continues running, for different wall structure, Wall structure 1 with light-weight structure has the biggest wall inner surface heat flow decrease ratio in summer. Then is wall structure 2, wall structure 3, wall structure 4. Namely, the wall with worse heat storage capacity, the PCM layer has a better improvement effect for wall thermal performance. For example, in summer, the inner surface decrease rate of wall structure 1 is 44.3%; However, for heavy-weight wall structure 4, the value is just 15.6%.

(4)When air conditioning is intermittent running, PCM layer in wall inner surface not only cannot improve wall inner surface temperature and heat flow response rate, but also decrease wall inner surface thermal response rate. When PCM layer is in wall outer surface, the thermal response rate can be increased in a certain extent. When light-weight wall with PCM layer in inner surface, heat flow can increased by above 200%, however, for inner surface, it can be decreased by 10%~ 20%.

(5)Compared with continues running mode, inner surface heat flow reduction rate of middle-weight and heavy-weight wall are separately averagely 64% and 60% under four intermittent running When air-conditioning is intermittent running. At the same time, for short- cycle intermittent running mode, the energy saving ratio is lower than that of continues running mode, and PCM layer in wall outer surface is superior than that in inner surface. For long-cycle intermittent running mode, the energy saving ratio is higher than that of continues running mode, and PCM layer in wall inner surface is superior than that in outer surface.

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Chapter Six: Case Study on Improvement of Thermal Performance of Wooden Walls Integrated with PCMs layer in Japan

6. 1 Introduction

After the Great East Japan Earthquake, the percentage of fossil fuels has been increasing in Japan, as a substitute for nuclear power as fuel for power generation. The level of dependence on petroleum which had been on a declining trend in recent years increased to 47.3% in fiscal 2012. As a result, the government has been working to construct energy policies aiming to provide a stable energy supply and lower energy costs. In this process, the introduction of energy saving and renewable energy has been promoted, and reviews are being conducted in a direction toward lowering the level of dependence on nuclear energy. In the other hand, the energy consumption of the building sector has increased 2.5 times (household sector is 1.3 times) during 1973 to 2007, the highest increase compared to transportation (2.0 times) and industrial sector (1.0 times). The housing sector consumes energy more than double that of the time of the first oil crisis, while after the oil crisis, development of energy saving type home electronic appliances, gas apparatuses and so on were penetrating progressively to homes.

Many Japanese residential buildings are wood structure since ancient times, high temperature and humidity. Wood structures are always small thermal capacity and for make sure a high thermal storage capacity, always thermal storage materials such as concrete is used on building envelops such as walls, floors and ceilings. However, these materials has a obviously increase of building self-weight with sensible thermal storage capacity. So many Japanese researchers began to make research on building envelops with PCM as a passive energy saving methods. Most of research are that PCM materials is mixed with other building materials. Dr. Takeshi KONDO et [1-2] made study on the thermal storage of PCM wallboard and make the measurements of thermal behavior and the effect on indoor environment in Tokyo in 2001. Hiroshi TAKEDA[3] made research on application of phase change materials (PCM) to building heating, verification of room temperature fluctuation constructed by wall with built-in PCM bag. Yuki SATO [4] made research on the reduction effect of the space heating load by installing PCM on interior building walls by a model box experiment. Dr. SOEDA Haruo. et make series study on indoor thermal environments control with phase change materials.[5-6] However, it is also under experimental period and have not been applied in a large scale.

So In this chapter, we make analysis on the energy saving of a wooden multi-wall with PCM layer under the Fukuoka whole year climate when the PCM layer in different location of the wall. Among which, the typical period in summer (7.16~7.20) and winter (1.16~1.20) is selected for future analysis. In addition, the influence of heat conductivity coefficient and heat latent of the PCM on the wall energy saving is analyzed.

6.2 Research object

A wooden multi-wall of residential building of Japan is selected in this chapter as shown in Figure 6-1. Among which, Wall 1 is a original wall without PCM layer, Wall 2 and Wall three are multi-wall with PCM layer in different location. Table 6-1 shows the thermal physical properties of every wall layer.

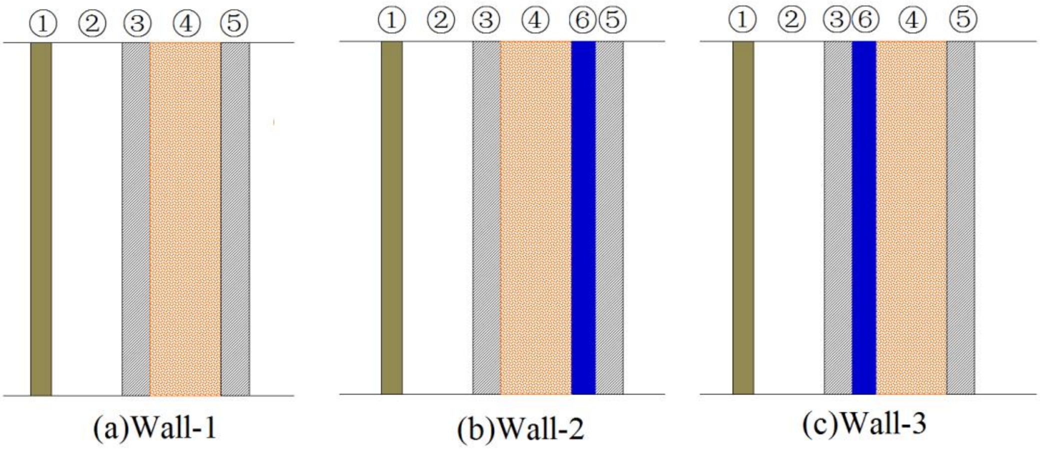


Figure 6-1 Section of the typical wall (a) Wall-1 without the PCM layer; (b) Wall-2 with the PCM layer in the outside of the insulation layer; (c) Wall-2 with the PCM layer in the inside of the insulation layer; (from outside to inside)

Table 6-1 Thermal physical properties of wall material

Materials	Density (kg/m3)	Heat capacity (J/(kg·K))	Heat conductivity coefficient (W/(m·K))	Thickness (mm)
①Plaster layer	1860	840	0.87	9
②Air layer	1.29	1012	0.02	30
③⑤Plywood	750	1050	0.12	12
④Insulation materials	23	1280	0.034	12
⑥PCM	1300	1785	0.6	10

6.3 Outdoor climate data and indoor temperature setting

For the situation in Japan, climate data of Fukuoka is selected for the numerical simulation. Figure 6-2 shows the whole year hourly outdoor temperature and solar radiation. The indoor setting air temperature which is obtained according equation (4-14), if the indoor air temperature from Equation. (4-14) is greater than 25 ℃ in summer, indoor air temperature is set as 25 ℃. Meanwhile, if the indoor air temperature from Equation. (4-14) is less than 20 ℃ in winter, indoor air temperature is set as 20 ℃. And indoor temperature setting is shown in Figure 6-3.Other setting of boundary condition is same with the situation in Chapter four.

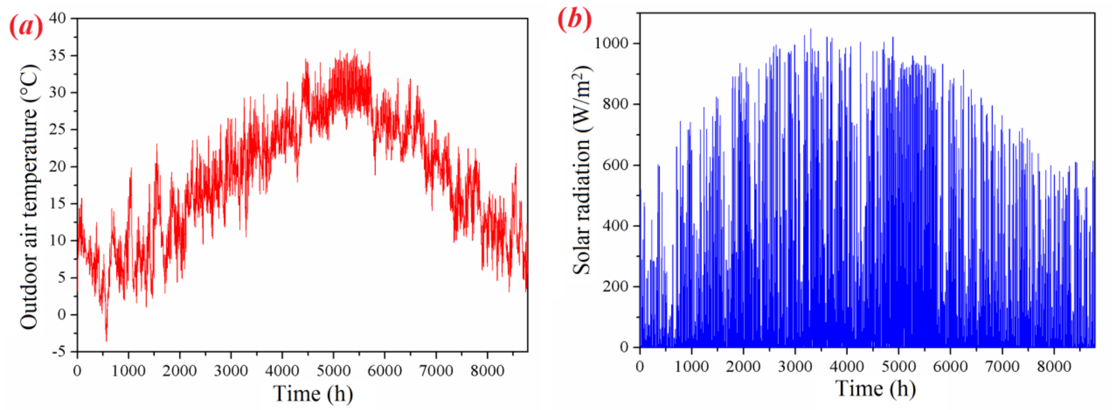


Figure 6-2 Variation of outdoor air temperature and solar radiation

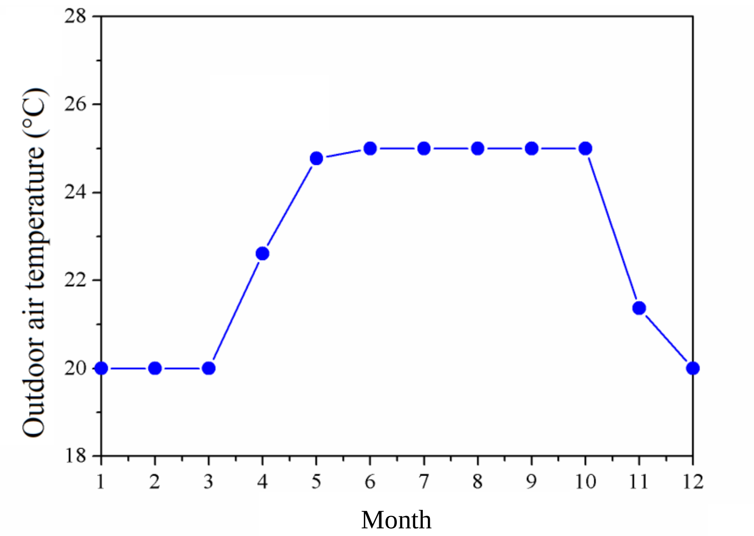


Figure 6-3 Variation of mouthy design temperature of indoor air

6.4 Results analysis

Theory phase change range suitable for Wall 2 and Wall 3 is got according the equation ((3~15)and (3-16)) according the whole year climate condition. The phase change range of Wall 2 is 2.89^{o}C~43.84 ^{o}C. And for Wall 3, the phase change range is 16.9 ^{o}C~28.85 ^{o}C.

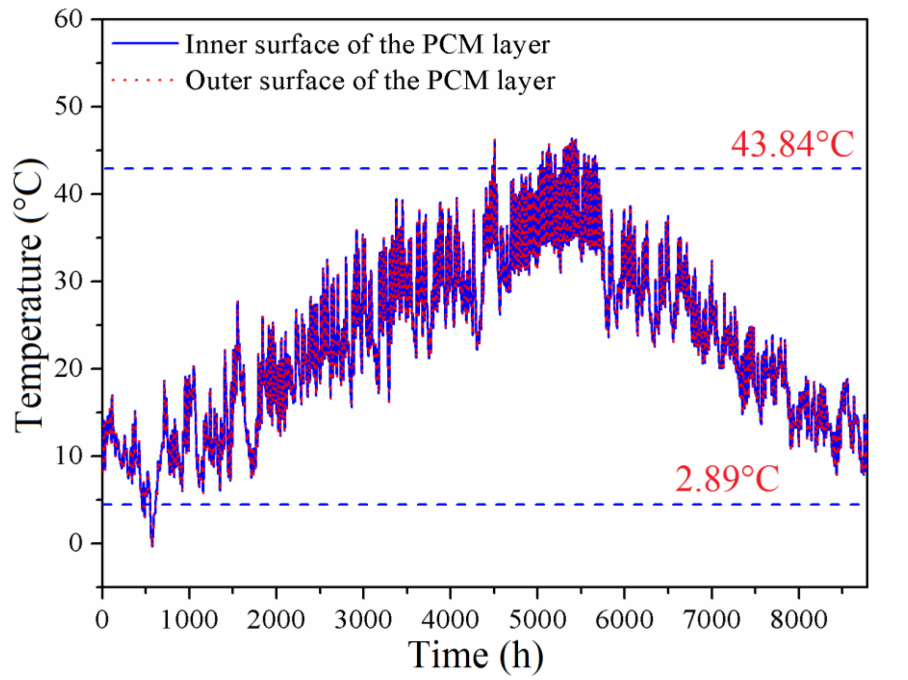


Figure 6-4 Variation of surface temperature of the PCM layer in the whole year for Wall -2

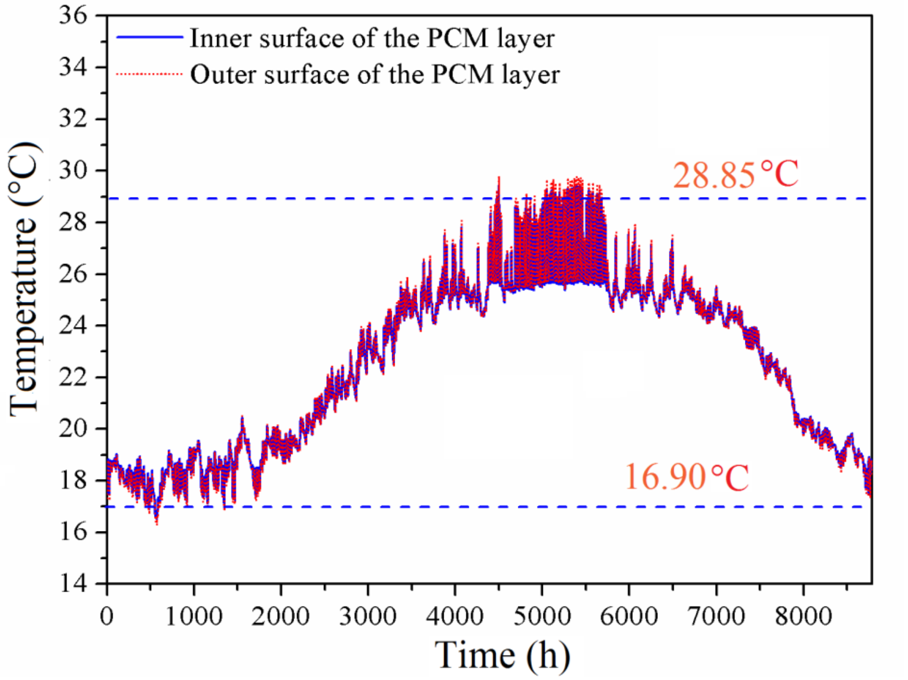
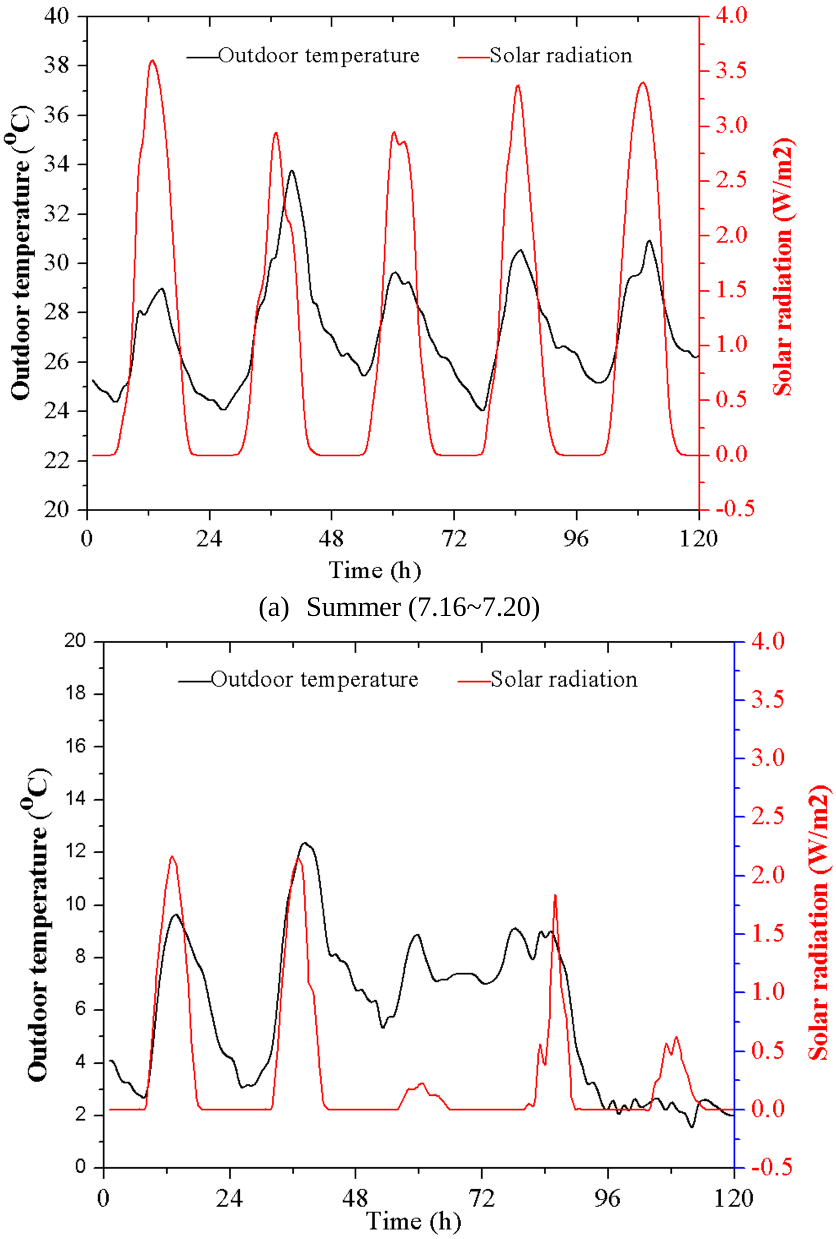


Figure. 6-5 Variation of surface temperature of the PCM layer in the whole year for Wall -3

Figure 6-4 and Figure 6-5 shows the shows the variation inner surface and outer surface temperature of PCM layer in the whole year for Wall-2 and Wall3. From the figure, it can be found that most time of the PCM layer temperature is in the phase change range in the whole year and the phase change range for Wall 3 is more narrow. In order to make future analysis on effect of PCM on the wall thermal performance more clearly, typically preventative of summer (7.16~7.20) and winter climate (1.16~1.20) are selected as shown in Figure 6-6.



(a) Summer (7.16~7.20)

(b) Winter (1.16~1.20)

Figure 6-6 Outdoor typical climate condition in summer (7-16~7.20) and in winter (1.16~1.20)

6.4.1 Improvement of thermal performance of wooden walls integrated with PCMs layer under different PCM layer location

Figure 6-7 shows the variation of inner surface temperature of three walls in (a) typical summer condition and (b) typical winter condition. From the data processing of the figure, it can be found that the temperature peak value in summer can be decreased by 60.54% and 40.36% for Wall 2 and wall 3 in summer. In Winter, the temperature peak value can be decreased by 65.9% and 34.98%. and the peak time delayed time can be up to 3.6~4h. Above result shows that PCM can improve indoor thermal comfort. The effect is better when PCM layer is in the inside of insulation layer.

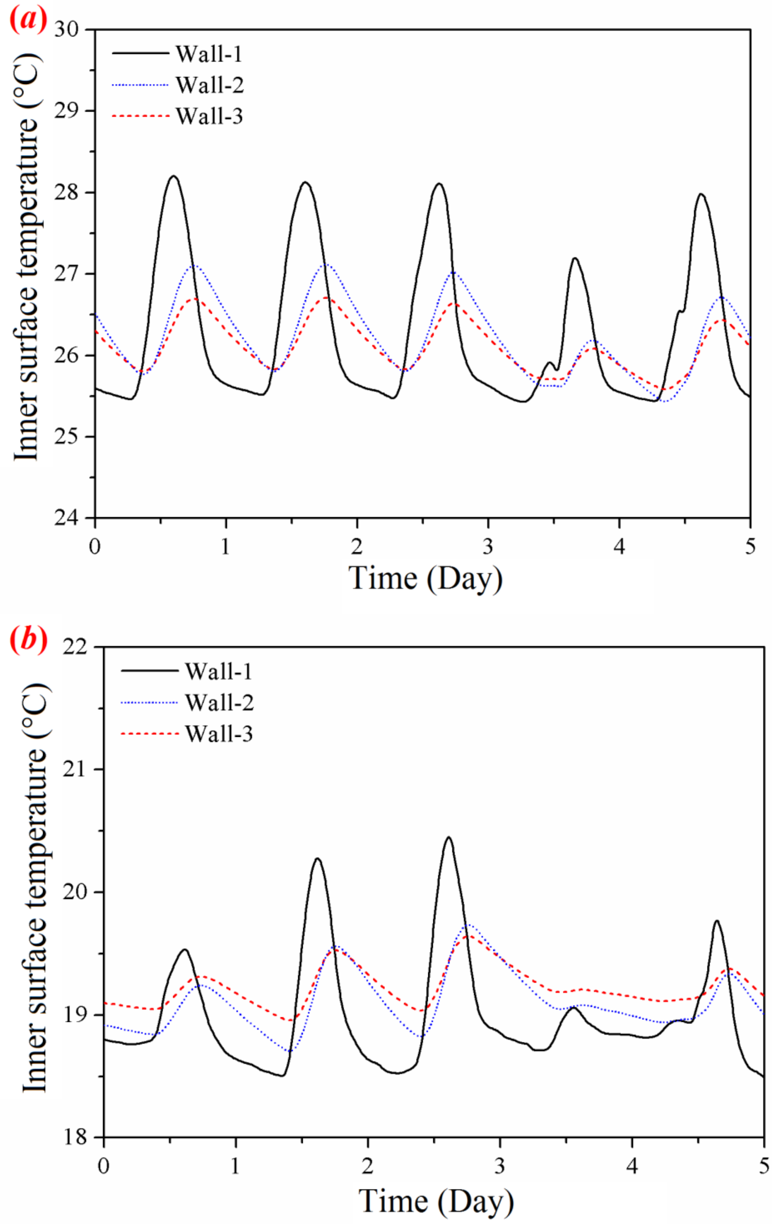


Figure 6-7 Variation of the inner surface temperatures for three walls of the PCM layer under (a) the summer conditions and (b) the winter conditions

Figure 6-8 shows the variation of inner surface heat flow of three walls in (a) typical summer condition and (b) typical winter condition. From the figure, it can be found that the same with the variation of inner surface temperature, PCM layer can enhance the stability of wall inner surface heat flow, and thereby improve the running efficiency of heating and air-conditioning equipments and then decrease the city electric load.

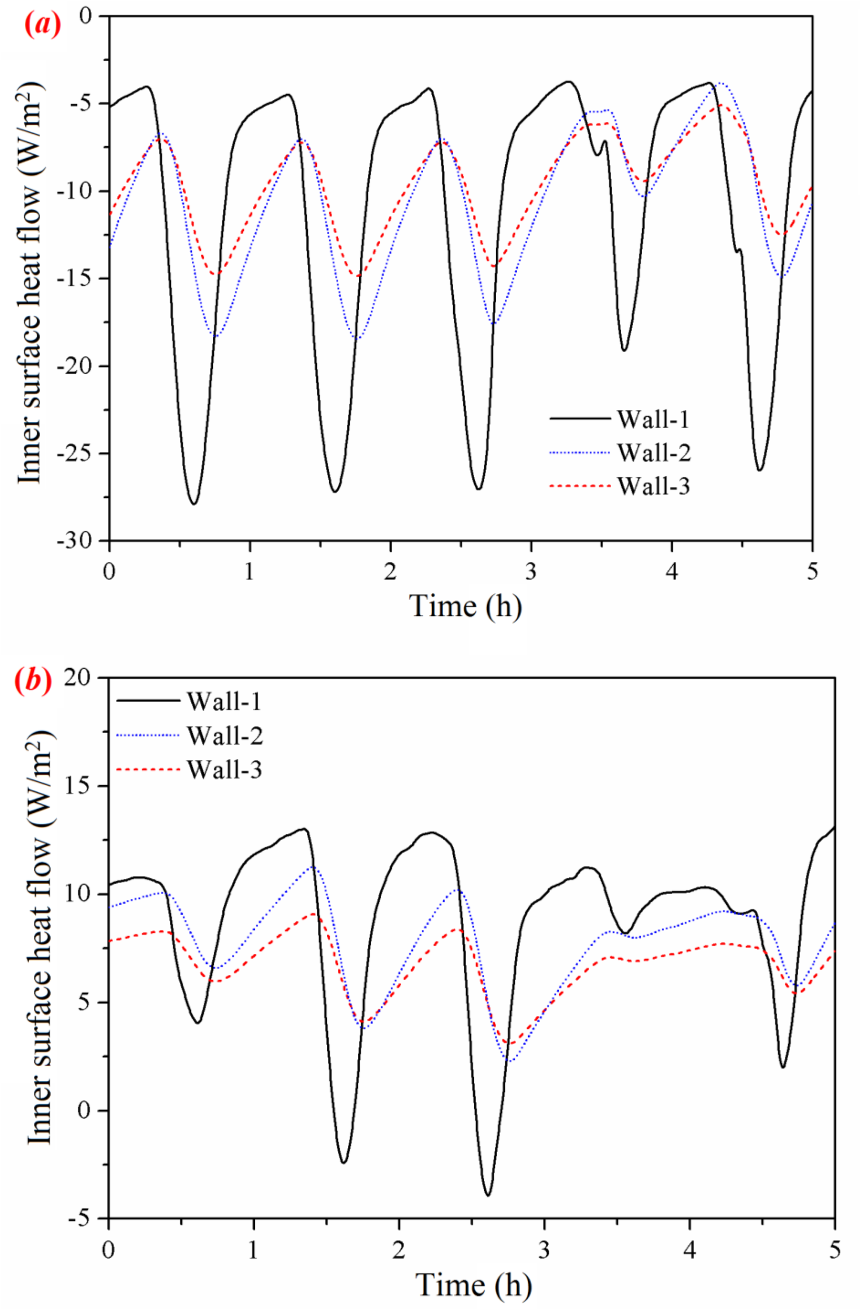


Figure 6-8 Variation of the inner surface heat flows for three walls of the PCM layer under (a) the summer conditions and (b) the winter conditions

Figure 6-9 shows the inner average inner surface heat flow reduction during the typical summer and winter condition. It can be found that in summer, compared with wall 1, the average heat flows can be decreased by 4.29% and 13.27% for Wall 2 and Wall 3. In winter , the reduction value is 11.14 % and 22.65% . Therefore, no matter in summer or winter, wall 3 has a better energy conservation effect. So the analysis in follow paragraph is aiming at Wall 3.

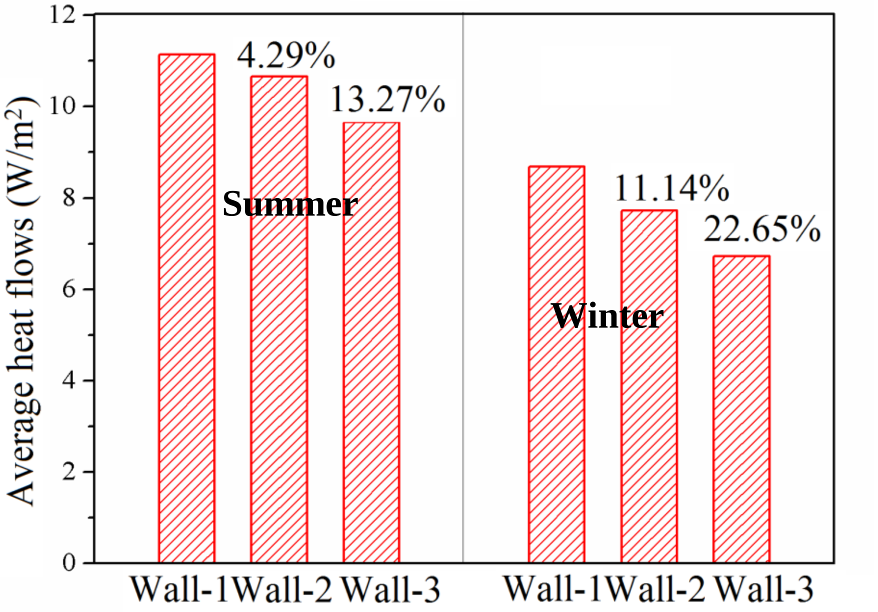


Figure 6-9 Comparison of the inner surface heat flow reduction for three walls compared with Wall1

6.4.2 Improvement of thermal performance of wooden walls Integrated with PCMs layer under different PCM heat conductivity coefficient

Figure 6-10 and 6-11 shows wall inner surface temperature and heat flow for Wall 3 when the PCM heat conductivity coefficient is different. However, results shows that no matter in summer or in winter, wall inner surface heat flow are basically same, so there have no influence of PCM heat conductivity coefficient on wall energy consumption. The main reason for this phenomenon is that even the PCM heat conductivity increased from 0.2 to 0.8, it is a small value for the heat conductivity of the whole wall. So PCM should use its phase change capacity at most content rather than insulated capacity.

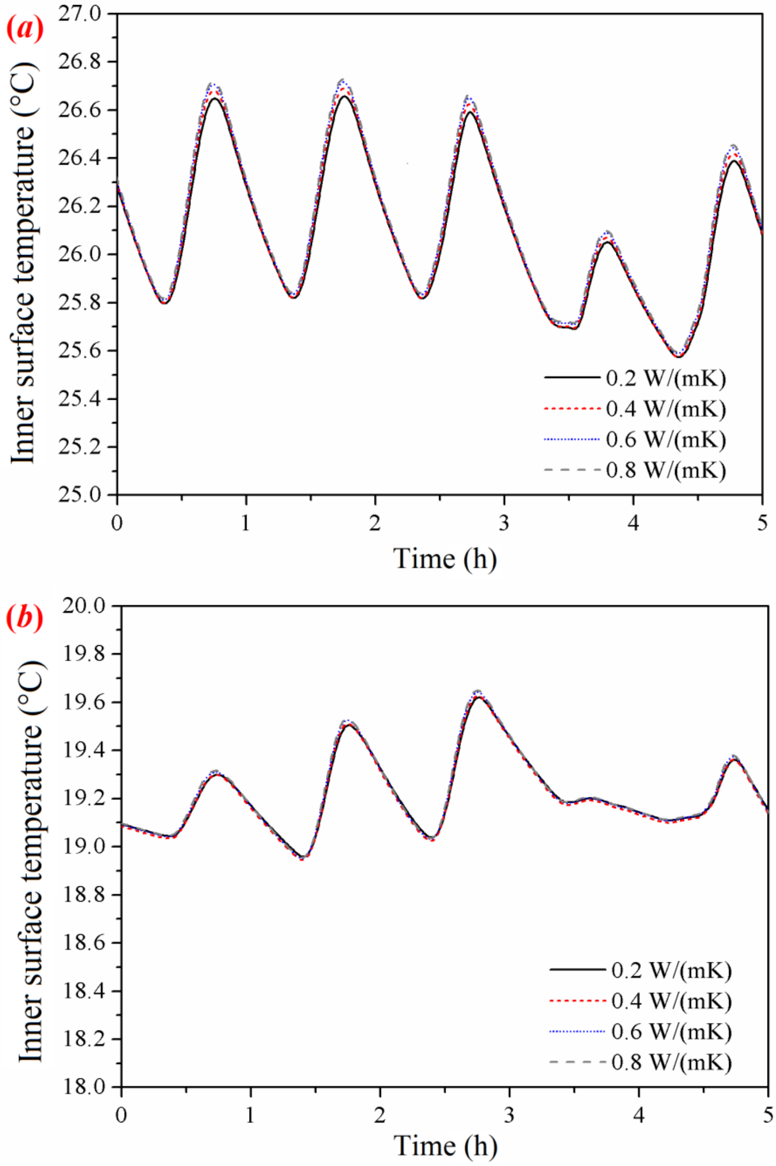


Figure 6-10 Variation of the inner surface temperaure for the different heat conductivity coefficient under (a) summer conditions and (b) winter conditions

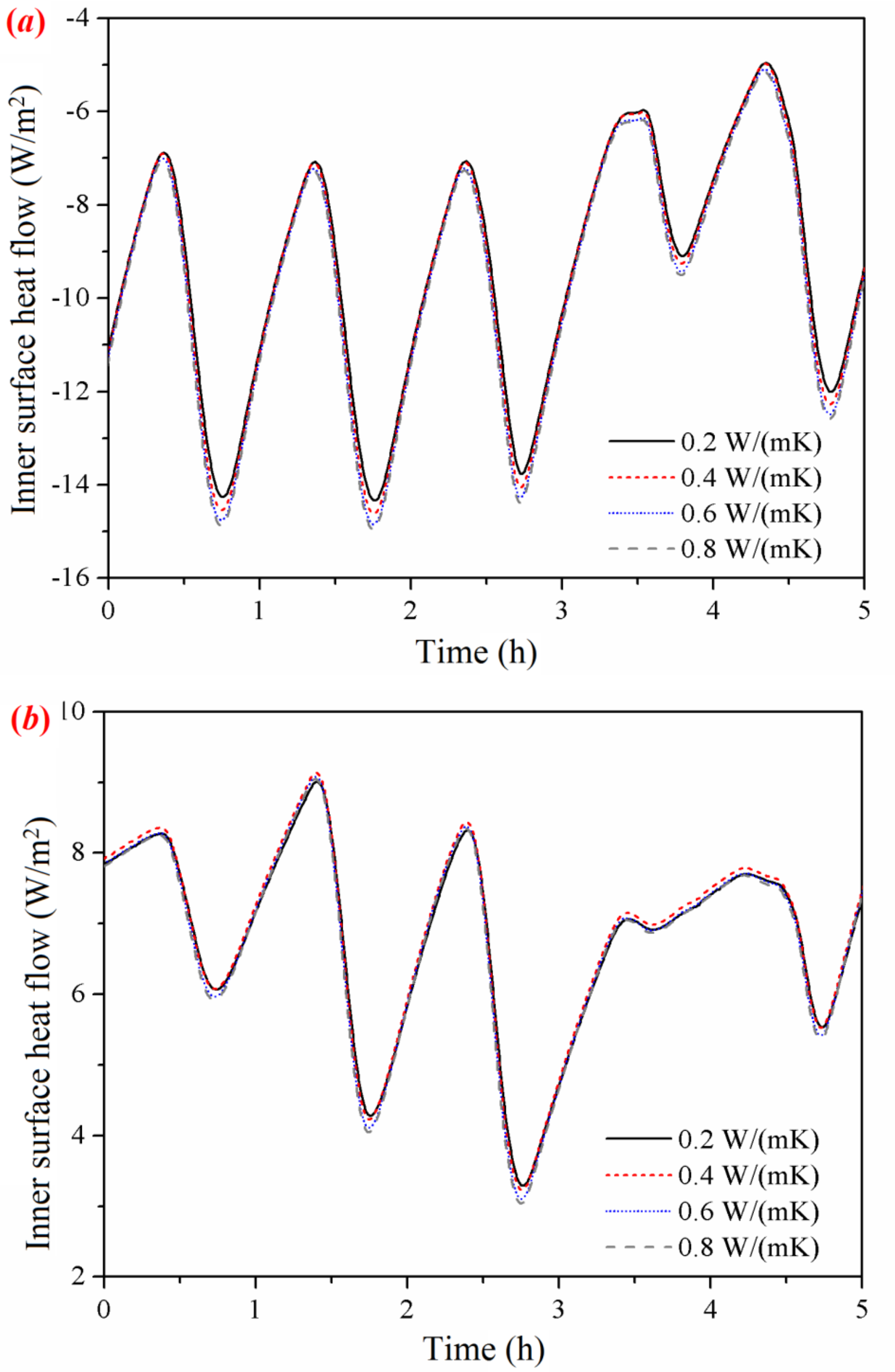


Figure 6-11 Variation of the inner surface temperatures for the different heat conductivity coefficient under (a) summer conditions and (b) winter conditions

6.4.3 Improvement of thermal performance of wooden walls Integrated with PCMs layer under different PCM heat latent value

Figure 6-12 shows the variation of the inner surface temperatures for the different latent heat under (a) summer conditions and (b) winter conditions. It can be found that with the increase of phase change heat latent, indoor temperature amplitude decreases obviously; compared with PCM heat latent value 50kJ/kg, multi-wall with PCM layer with heat value 200 kJ/kg inner surface temperature peak decreases by above 60%. Under Fukuoka climate condition, for the wall structure in this chapter when phase change heat latent increase to above 150kJ/kg, there is little reduction effect for wall inner surface temperature even continue increasing the heat latent value.

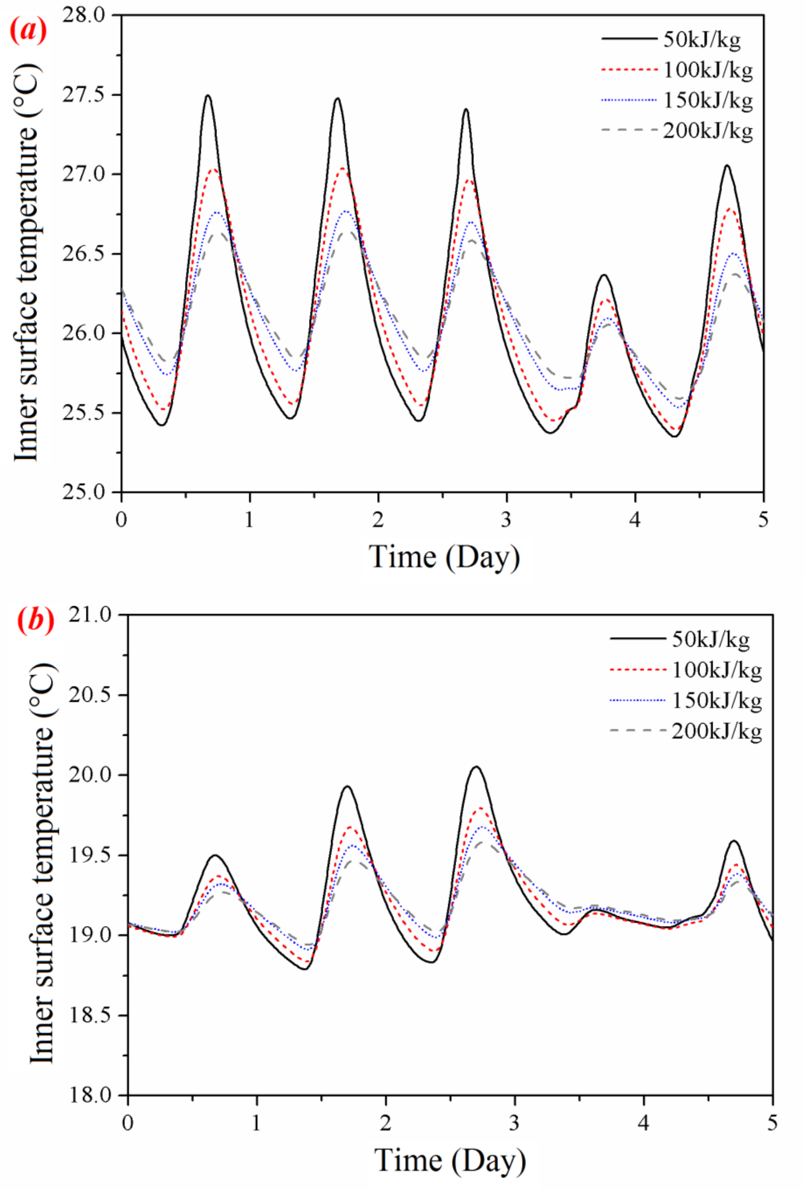


Figure 6-12 Variation of the inner surface temperatures for the different latent heat under (a) summer conditions and (b) winter conditions

Figure 6-13 shows Comparison of the inner surface heat flow reduction for the different latent heat under (a) summer conditions and (b) winter conditions. The variation rule is same with the variation of inner surface temperatures.

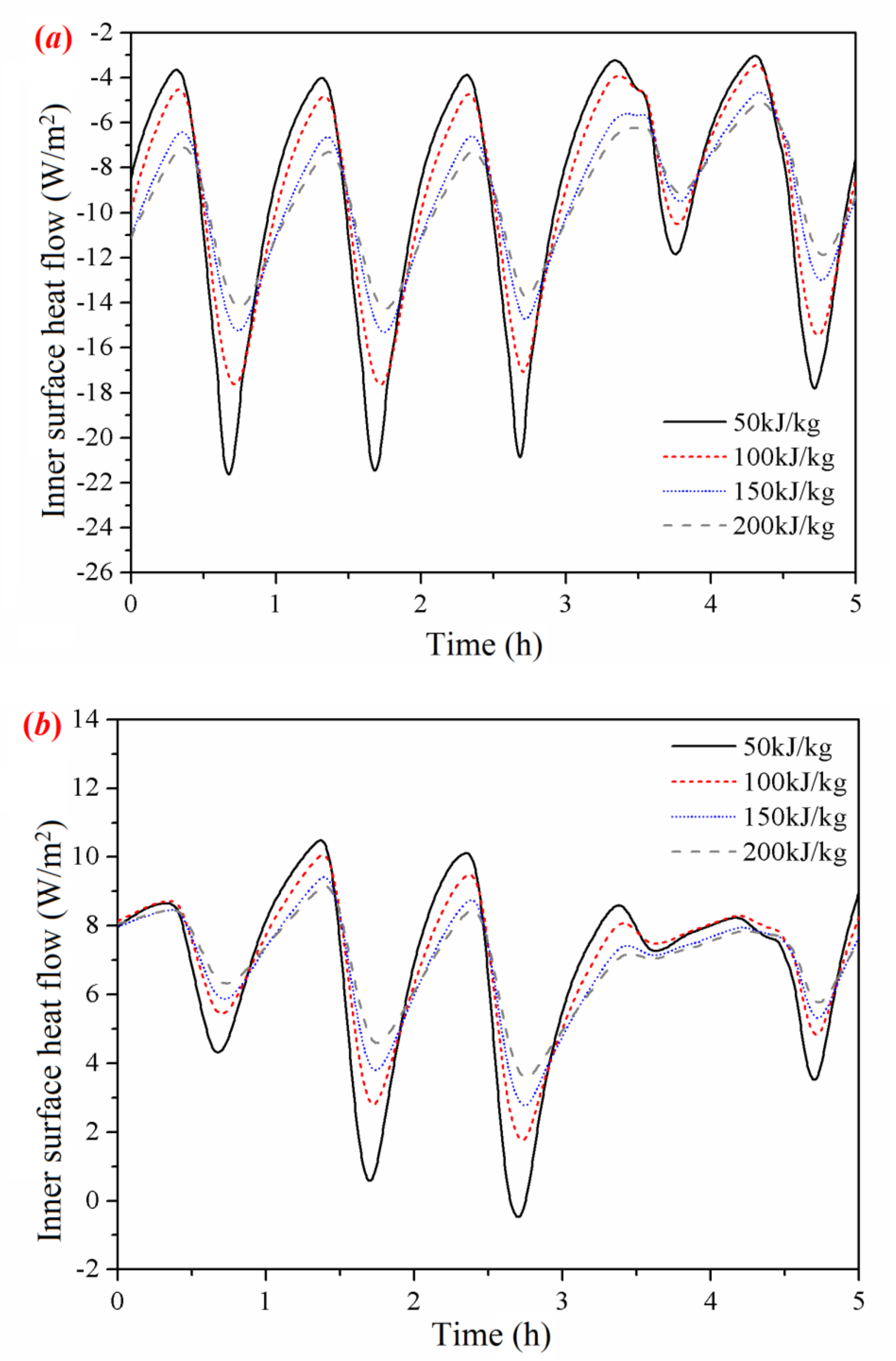


Figure 6-13 Comparison of the inner surface heat flow reduction for the different latent heat under (a) summer conditions and (b) winter conditions

Figure 6-14 is the comparison of the inner surface heat flow reduction for the different latent heat. It can be found that no matter in summer or in winter, the average heat flows reduction caused by latent heat is very small. The reason is the PCM layer increase wall thickness and thermal inertia, its function of decreasing indoor temperature and improving wall thermal stability is small.

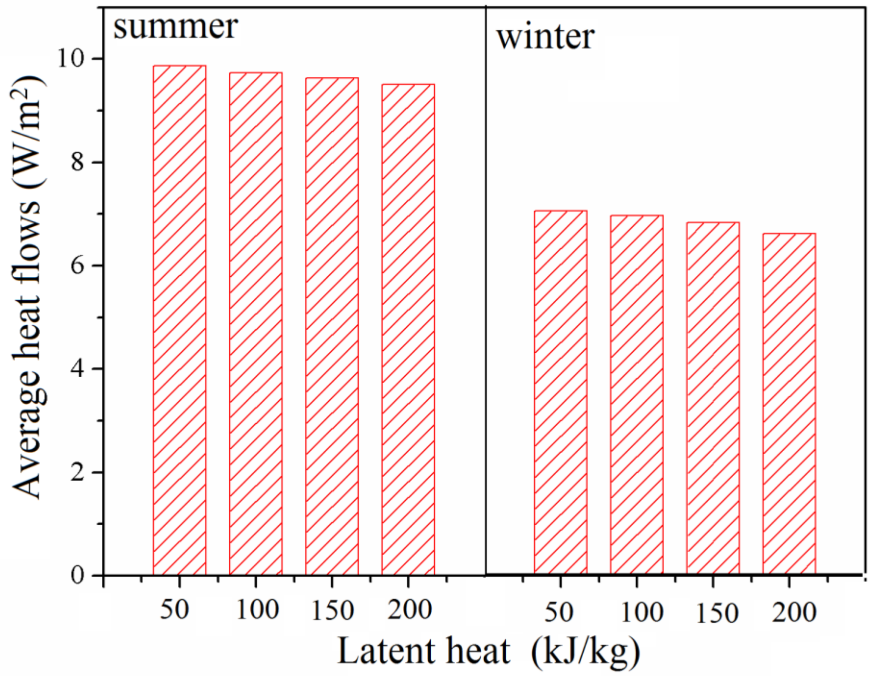


Figure. 6-14 Comparison of the inner surface heat flow reduction for the different latent heat

6.5 Summary

In this chapter, we make analysis on the energy saving of a wooden multi-wall with PCM layer under the Fukuoka whole year climate when the PCM layer in different location of the wall. Among which, the typical period in summer (7.16~7.20) and winter (1.16~1.20) is selected for future analysis. In addition, the influence of heat conductivity coefficient and heat latent of the PCM on the wall energy saving is analyzed. Conclusions can be obtained as follows:

(1) In summer, compared with wall 1, the average heat flows can be decreased by 4.29% and 13.27% for Wall 2 and Wall 3. In winter , the reduction value is 11.14 % and 22.65% . Therefore, no matter in summer or winter, wall 3 has a better energy conservation effect.

(2) PCM heat conductivity coefficient has little influence on wall energy saving for the wall structure under the climate condition in this chapter.

(3) Decrease of PCM heat latent can decrease the wall inner surface temperature and heat flow peak value, however, the reduction for the average heat flow is small.

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Chapter Seven: Conclusions

According to the investigation of the world energy consumption, world building energy consumption and current thermal storage technologies, we found that phase change materials (PCMs) is helpful for energy conservation when it is used in building envelopes. So this paper introduce the basic concept about PCMs used in buildings and investigates the research statue of PCM in buildings in Japan and China. Then the confirming method of PCM phase change range is proposed theoretically. Based on that, the improvement effect of wall thermal performance with PCM layer in China and Japan is analyzed. All conclusions are summarized as follows:

In Chapter One, investigates the global energy consumption situation, global building energy consumption situation and thermal energy storage(TES) technology, the previous studies about the PCM application in buildings is reviewed.

In Chapter Two, firstly, the basic properties of PCMs are introduced. Then the development of PCMs in building envelops is investigated. PCM in building walls are firstly applied in passive solar wall-PCM enhanced Tromb wall. After that, the application research on concrete block with PCM, PCM-enhanced gypsum board and light-weight wall integrated with PCM are began to be researched. Then the research status of PCMs in buildings in Japan and China have been investigated. The PCMs in buildings envelop now are under the period of research and experiment in Japan and lacking application in real engineers. Most researches focus on wood structure residential buildings envelops with PCMs layer because wood structures' small thermal capacity. Most research are under Tokyo climate condition. In china, PCMs are always used in light-weight wall, concrete block, and gypsum plaster. And results show that PCMs can increase wall thermal inertia and the increase indoor thermal comfort and save air-conditioning load and heating load.

In Chapter Three, According the rule of PCMs phase change in building walls, principle of PCM phase change range is proposed. Then based on the theory analysis of heat transfer laws, the calculation equations of phase-change range of PCMs in multi-layer wall are got. According to the equation, factors influencing the PCMs phase change range including outdoor thermal environment and wall structure have been analyzed qualitatively. Results show that with the increasing of summer outdoor temperature and outdoor fluctuation, liquids temperature of PCM layer increase linearly. The moving of PCM from wall inner surface to outer surface (namely increase of L) lead to the whole phase change range decrease. The nearer PCM layer to wall inner surface, the lower liquidus temperature, higher solidus temperature and smaller phase change slope. The increase of thickness of wall sintered brick layer is helpful for solidus temperature increase and liquidus temperature decrease. The heat conductivity coefficient of wall sintered brick layer helps the PCM phase change range increases.

In Chapter Four, a heat transfer model of multi-layer wall integrated with PCMs layer is established to make verification of theoretical calculation method of PCM layer phase change range in Chapter Three. The model is verified by experiment in Chengdu, China. The covering rate of the wall surface temperature is used to evaluating the accuracy of the calculating method. After that, the optimum verification is done under different design periods of phase-change occurrence, different position of the PCM layer in multi-layer wall, different multi-wall structure. Under three above verification cases, the PCM phase-change range obtained from the theoretical algorithm can guarantee value of covering rate is between 90%~99%; thereby, PCM can improve the wall thermal properties by its heat-storage and discharge characteristics. On the other hand, whether the PCM phase-change range is reduced by 0.5 ℃ or increased by 0.5 ℃, the disadvantageous variation will happen on the inner surface heat flow, which indicates that the PCM phase-change range obtained from the theoretical algorithm is optimum.

In Chapter Five, quantitative analysis on improvement effect of PCMs on multi-layer walls thermal performance under air-conditioning continue running and intermittent running mode are completed under climate of Chengdu, China. When air-conditioning is continue running, no matter for light-weight walls or heavy weight walls, PCMs layer in wall inner surface has the best effect for the improvement of wall thermal performance. For the different location of PCM layer, the variation of wall inner surface temperature and heat flow is same and the closer of PCM layer to inner surface, the delayed time and wave peak decrease rate is bigger. For example, in summer, when PCMs layer is in wall inner surface, the decrease rate is 20.5% ; when PCMs layer is in wall outer surface, the decrease is 11.3%. For different wall structure, Wall structure 1 with light-weight structure has the biggest wall inner surface heat flow decrease ratio in summer. Then is wall structure 2, wall structure 3, wall structure 4. Namely, the wall with worse heat storage capacity, the PCM layer has a better improvement effect for wall thermal performance. For example, in summer, the inner surface decrease rate of wall 1 is 44.3%; However, for heavy-weight wall structure 4, the value is just 15.6%. When air conditioning is intermittent running, PCM layer in wall inner surface not only cannot improve wall inner surface temperature and heat flow response rate, but also decrease wall inner surface thermal response rate. When PCM layer is in wall outer surface, the thermal response rate can be increased in a certain extent. When light-weight wall with PCM layer in inner surface, heat flow can increased by above 200%, however, for inner surface, it can be decreased by 10%~ 20%. Compared with continues running mode, inner surface heat flow reduction rate of middle-weight and heavy-weight wall are separately averagely 64% and 60% under four intermittent running When air-conditioning is intermittent running. At the same time, for short- cycle intermittent running mode, the energy saving ratio is lower than that of continues running mode, and PCM layer in wall outer surface is superior than that in inner surface. For long-cycle intermittent running mode, the energy saving ratio is higher than that of continues running mode, and PCM layer in wall inner surface is superior than that in outer surface.

In Chapter Six, under the climate of Fukuoka, for the wooden wall structure, in summer, compared with wall 1, the average heat flows can be decreased by 4.29%, 13.27% for Wall 2 and Wall 3. In winter , the reduction value is 11.14 % and 22.65% . Therefore, no matter in summer or winter, wall 3 has a better energy conservation effect. PCM heat conductivity coefficient has little influence on wall energy saving for the wall structure under the climate condition in this chapter. Decrease of PCM heat latent can decrease the wall inner surface temperature and heat flow peak value, however, the reduction for the average heat flow is small.