ANALYSIS OF THERMAL ENERGY STORAGE SYSTEM FOR ENERGY SAVING RECONSTRUCTION OF BUILDING IN REGION WITH HEATING PROVISION AND HIGH SUNSHINE

by

Bingzhi WANG and Yanan LI *

Jining NO.1 People's Hospital, Jining, Shandong, China

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This research aims to analyze the effect of phase change energy storage wall on the internal thermal environment in high-sunshine passive solar residential buildings. The residential buildings in Lhasa are taken as research objects, and the differences in indoor and outdoor thermal environments of the residential buildings in winter are first evaluated. Then, the energy storage wall model based on phase change material is constructed, the meteorological data of the winter solstice day is used to simulate, and the changes of the thermal environment in the room are detected. The results showed that the average solar radiation intensity of the dwellings in Lhasa is 441.8 W/m², and the average scattering intensity is 156.3 W/m². The average humidity and temperature of outdoor air are 24.4% and 1.54 °C, respectively. The temperature difference of the indoor south and north bedrooms is 3.3 °C, the internal temperatures of the indoor south and north walls are 13.4 °C and 7.9 °C, respectively, and the temperature difference is 5.5 °C. After the adoption of phase change energy storage materials, the indoor temperatures of the south and north walls on the winter solstice day are 16.75 °C and 16.52 °C, respectively, with a temperature difference of 0.23 °C. The inner surface temperatures of the south wall and the north wall increase by 25.0% and 109.1%, respectively, after adopting the phase change energy storage wall, indicating that applying the phase change energy storage wall to the passive solar residential buildings in Lhasa can effectively improve the indoor thermal environment.

Key words*: passive solar residential buildings, thermal environment, phase change energy storage wall, high sunshine*

Introduction

Energy is an important resource for today's social progress and economic development. The daily life of human beings is also inseparable from energy. China has sufficient reserves of fossil energy and is a major producer and consumer of energy. Statistics show that as early as 2005, China's total coal energy consumption has exceeded 2.6 billionns, and by 2018, it has consumed about 4.6 billionns, with an annual compound growth rate of 4.5% [1, 2]. At present, China is in a period of rapid development. With the continuous development of the construction industry, the consumption of energy also shows a year-to-year growth trend, and the energy consumed by the construction industry has reached 36% of China's total energy consumption [3]. With the continuous expansion of urbanization, more and more energy will be consumed by the construction industry, which will undoubtedly aggravate the energy crisis.

* Corresponding author, e-mail: dabing-0105@163.com

Therefore, the development and utilization of renewable energy is of great significance to the protection of ecological environment and the realization of the goal of sustainable development. There are four types of solar energy resource zones in China. The total solar radiation received each year can reach 3340-8400 MJ/m^2, and the total solar radiation received in western China can reach 1750 kWh/m^2 or above [4-6]. Therefore, the development of passive solar heating buildings according to local conditions is conducive to easing the contradiction between human and natural environment.

Passive solar architecture is based on the orientation of the building and its natural environment. This method, which can reduce the total energy use of buildings such as heating by utilizing solar energy, is widely welcomed in rural areas because of its low price and other characteristics. However, with the continuous development of passive solar architecture, the building's disadvantages of poor thermal stability, poor comfort, and high temperature in summer are gradually exposed. Although the measures to increase the thermal resistance of the envelop such as thermal insulation curtain can improve the energy saving rate to some extent, there are still limitations. The phase change materials (PCM) is a kind of material that can absorb or release heat in the process of its physical state change, and can also make use of the heat in this part, so as to carry out heat storage and indoor temperature regulation [7-12]. The application of PCM and other heat storage materials in the heat storage of the envelope can effectively maintain the thermal stability of the building and reduce the cost of building materials to a certain extent.

However, the application of phase change energy storage wall in solar energy building will be affected by factors such as region and solar radiation intensity, so it is a complex problem that needs to be solved urgently.

Methods

Indoor environment testing of residential buildings

China is located between 18° and 54° north latitude, and has abundant solar energy resources. Every year, China can receive sunshine over 5800 MJ/m^2 and over 2200 hours. In addition Xinjiang and Tibet area, the total amount of sunshine radiation in the whole year in China is higher in the northern region than in the southern region, and higher in the western region than in the eastern region. Tibet has high altitudes and thin air, and the atmosphere has weaker ability to reduce solar radiation. Therefore, on the whole, Tibet region can receive more sunshine, and the annual solar radiation amount is the most, belonging to the area with high sunshine, which lays a foundation for the promotion of solar energy saving buildings. However, solar energy saving buildings can be divided into active and passive types. The former requires a large amount of investment in the early stage, its technology is complex, the utilization rate of the equipment is low, and the maintenance and management work of the equipment in the later stage is large. At this time, the advantages of passive solar energy saving buildings such as low cost, convenient management, and simple construction are more prominent, so they are widely used in residential buildings and some public buildings.

In this study, based on solar energy saving resources and other relevant factors, from December 20-30, 2017, the thermal environment of a residential building in Lhasa of Tibet is tested. The residential building faces south with a room height of 3.0 m. The outer wall and inner wall are composed of solid concrete blocks with a thickness of 3.4 dm and 2.4 dm, respectively. The roof is made of reinforced concrete slab with thickness of 2 dm, without insulation layer, while the windows are mainly made of single-glass aluminum alloy, and there is no auxiliary heat source in the room. In order to ensure the reliability of the test, it is required that the test is conducted on a sunny day and no electrical equipment is used indoors. During the test, indoor and outdoor air temperature and humidity, surface temperature of inner wall, solar radiation and scattering intensity are collected every 10 minutes to explore the indoor thermal environment of solar energy saving buildings.

Evaluation index of indoor thermal environment of energy-saving residential buildings

The indicators used to evaluate indoor thermal environment include indoor air temperature, effective temperature (ET*), standard effective temperature (SET), Fanger thermal comfort equation, predicted thermal sensation index (predicted mean vote-predicted percentage dissatisfied PMV-PPD), subjective temperature, and operating temperature.

First, the Fanger thermal comfort equation is:

$$\Delta q = \left(t, \varphi, \overline{t}, v, m, R_c\right) = 0 \tag{1}$$

where t [°C] is the temperature in air, φ [%] – the relative humidity, $\overline{t}$ [°C] – the average radiation temperature, v [ms^{-1}] – the velocity of air-flow, m – the metabolic rate, and R_c – the thermal resistance of clothing.

Second, the calculation equation of PMV-PPD:

$$PPD = 100 + 95_{\text{exp}}\left(0.03353PMV^4 + 0.217PMV^2\right)L \tag{2}$$

where $\Delta q = 0$ means that the human body is in a state of heat balance, L – the thermal load of human body, and PMV is the generally divided into 7 grades, namely 3 (very hot), 2 (hot), 1 (slightly hot), 0 (moderate), –1 (slightly cold), –2 (cold), and –3 (very cold). Then ISO7730 recommends that when PMV > 0-0.5 and <0.5, it is an acceptable thermal environment.

Third, the calculation equation of subjective temperature:

$$t_a = 33.5 - 3R_c - \left(0.08 + 0.05R_c\right)m \tag{3}$$

Fourthly, the calculation equation of operating temperature:

$$t_0 = \frac{ht + h't'}{h + h'} \tag{4}$$

where t [°C] is the indoor temperature, t' [°C] – the average indoor radiant temperature, h [Wm^{-2}°C^{-1}] – the convection heat transfer coefficient, and h' [Wm^{-2}°C^{-1}] – the radiation heat transfer coefficient.

According to regulations, residential buildings with centralized heating need to be built in frigid or cold areas in China, and the average indoor temperature needs to be about 16 °C in thermal design. However, the heating measures in rural areas are all self-built, so this method is not applicable to all northwest areas. In the design of passive solar heating buildings, the indoor temperature should be 14-15 °C in winter, the indoor temperature fluctuation should not exceed 10 °C in a day, and the indoor temperature should not be less than 10 °C at night.

Construction of heat transfer model of phase change heat storage wall

Adding PCM to the wall and applying it to the solar building can effectively change the indoor thermal environment. Because the PCM will absorb or release a considerable amount of heat energy at the same time when the temperature is constant and will transfer the heat energy to the wall, the heat transfer model of the heat storage wall based on the PCM is constructed in this study. The human effects of solar radiation on buildings are uneven, so the meteorological data of the winter solstice in Lhasa are used to calculate the outdoor comprehensive temperature. The calculation equation of outdoor comprehensive temperature:

$$T_O = T_e + \frac{I\rho - q_e}{\alpha_\alpha} \tag{5}$$

where I [Wm^{-2}] is the total solar radiation received by the outer surface of the enclosure structure per unit area, ρ – the solar absorption rate of the outer surface of the envelope structure (0.7), q_e [Wm^{-2}] – the effective radiation, α_α [Wm^{-2}K^{-1}] – the total heat transfer coefficient of the wall surface, about 23.3 W/m^2/K in winter.

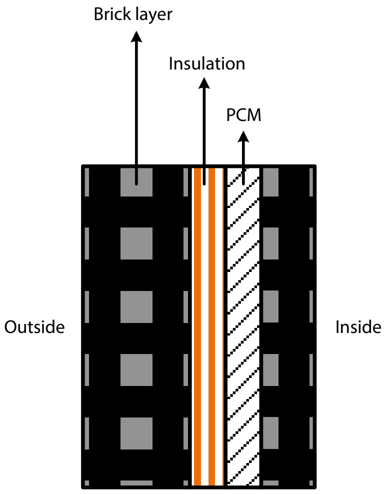

Figure 1. Heat storage wall model based on PCM

In this study, the structure of phase change energy storage wall is constructed, as shown in fig. 1. The brick layer is made of brick masonry with a thickness of 110 mm, a density of 1700 kg/m^3, specific heat of 0.8 kJ/kg/°C, and thermal conductivity of 0.84 W/m/°C. The insulation layer is made of a 40 mm sheet of renewable polystyrene with a density of 20 kg/m^3, a specific heat of 1.38 kJ/kg/°C, and a thermal conductivity of 0.041 W/m/°C. The PCM has a thickness of 20 mm, a density of 1558 kg/m^3, and a thermal conductivity of 0.58 W/m/°C.

In addition, in this study, the heat transfer coefficients of casement windows with single-glass, aluminum alloy doors, energy-saving roof, and floor are 2.3, 2.5, 0.41, and 0.51 W/m^2/°C, respectively. It can be observed that the heat transfer coefficient on the inner surface of the enclosure is 8.7 W/m/°C, and the heat transfer coefficient on the outer surface is 23.0 W/m/°C.

The average indoor air temperature and the average integrated outdoor temperature of the building are obtained after testing, and then the average temperature of the inner surface of the wall is calculated. The specific calculation equation:

$$\overline{\theta} = \overline{T}_I - \left(\overline{T}_I - \overline{T}_O\right)\frac{R_I}{R_0} \tag{6}$$

where $\overline{T}_I$ [°C] is the average indoor air temperature, T_O [°C] – the average integrated temperature of outdoor air, R_I [m^{2}KW^{-1}] – the heat transfer resistance of the inner surface of the wall , R_0 [m^{2}KW^{-1}] – the heat transfer resistance of the envelope. Then, the comprehensive outdoor air temperature is calculated by adopting the temperature data of the winter solstice in Lhasa. Moreover, based on the built phase change energy storage wall model, simulation is conducted to detect the temperature of indoor interior surface of the wall facing different orientations and the indoor air.

Results

Features of passive solar buildings in different regions

Generally, the main heat collection structure of passive solar energy building is vertically arranged in the south. Therefore, the irradiance temperature difference ratio (ITR) to the south and the solar irradiance, *I*, in the south are selected as indicators of division. The climate in the heating area can be divided into four types, as shown in tab. 1.

Table 1. Climate division of passive solar heating area

Partition		ITR [Wm^{-2}°C^{-1}]	*I* [Wm^{-2}]	Typical cities
Best	SH Ia	≥ 8	≥ 160	Lhasa, Shigatse, Qamdo
	SH Ib	≥ 8	<160, ≥ 60	Kunming, Dali, Kowloon
Suitable	SH IIa	< 8, ≥ 6	≥ 120	Xining, Yinchuan, Dunhuang
	SH IIb	< 8, ≥ 6	< 120, ≥ 60	Kangding, Jiuquan, Zhaotong
	SH IIc	< 6, ≥ 4	≥ 60	Beijing, Tianjin, Shijiazhuang
General	SH III	< 4, ≥ 3	≥ 60	Urumqi, Shenyang, Jilin
Inappropriate	SH IVa	≤ 3	–	Chengdu, Chongqing, Nanyang
	SH IVb	–	< 60	Suining, Nanchong, Daxian

The main heat collection devices used in buildings are direct beneficiary window, heat collection and storage wall, and heat storage roof. The most common heating methods in rural areas are direct beneficiary window and heat collection and storage wall, *etc*. After mixing these two methods, economic heating methods can also be obtained.

Testing results of indoor and outdoor thermal environment of original residential buildings

In this study, the outdoor thermal environment test of residential buildings is conducted first, and the results are shown in fig. 2. It can be observed from fig. 2(a) that the outdoor temperature peaks around 14:00 on the test day, and the maximum temperature is around 4.2 °C, and the temperature reaches a trough at 24:00, and the lowest temperature is around –2.1 °C. The air temperature difference between day and night reaches 6.3 °C, and the average air temperature on the test day is 1.54 °C. The relative humidity in the air reaches its peak around 11:00 (about 43.5%) and reaches a trough at 0:00 (about 16.1%). The air humidity difference between day and night reaches 27%, and the average relative humidity is 24.4%. It can be found that the region is cold and dry in winter, the temperature difference between day and night is large, and the relative humidity is low. As can be observed from fig. 2(b), the sunshine time on the test day is about 8h, and the solar radiation peak peaks at around 14:00, with the

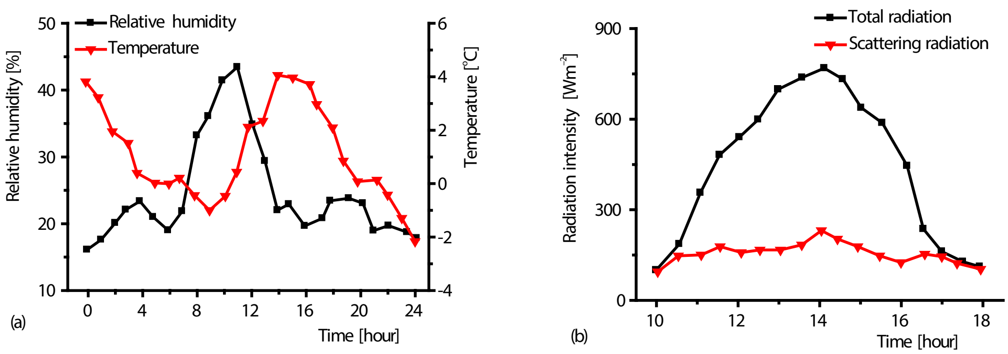

Figure 2. Variation of outdoor air temperature and humidity and solar radiation intensity; (a) shows the change of outdoor air temperature and humidity, (b) shows the variation of outdoor solar radiation intensity

highest radiation intensity of 768.7 W/m^2 and the average radiation intensity of 441.8 W/m^2. The scattering intensity of the sun also reaches its peak around 14:00, with the highest scattering intensity of 231.1 W/m^2 and the average scattering intensity of 156.3 W/m^2. The radiation intensity of direct solar radiation accounts for 67.6% of the total radiation intensity, indicating that the solar radiation intensity in the region is higher in winter.

The internal and external surface temperatures of the north and south walls are tested, and the results are shown in fig. 3. As can be observed from fig. 3(a), the temperature change trend of sitting room, south bedroom, and north bedroom is basically consistent, and because the sitting room is also located in the south, the temperature difference of the sitting room and south bedroom is not big therefore. The average temperature in the sitting room is 12.2 °C, the average temperature in the south bedroom is 13.1 °C, and the average temperature in the north bedroom is 9.8 °C. The difference in temperature between the north bedroom and the south bedroom is 3.3 °C. As can be observed from fig. 3(b), the external temperature of the south wall fluctuates greatly, with the highest temperature around 14:00 (about 21.7 °C) and the lowest temperature around 7:00 (4.2 °C). The temperature difference is 17.5 °C, and the average external temperature of the south wall is 9.5 °C. The average temperature outside the north wall is only 3.8 °C, and the temperature difference is 4.6 °C. The average temperature inside the south wall is 13.4 °C, and the temperature difference is 6.2 °C. And the average temperature inside the north wall is 7.9°C, with a temperature difference of 1.5 °C.

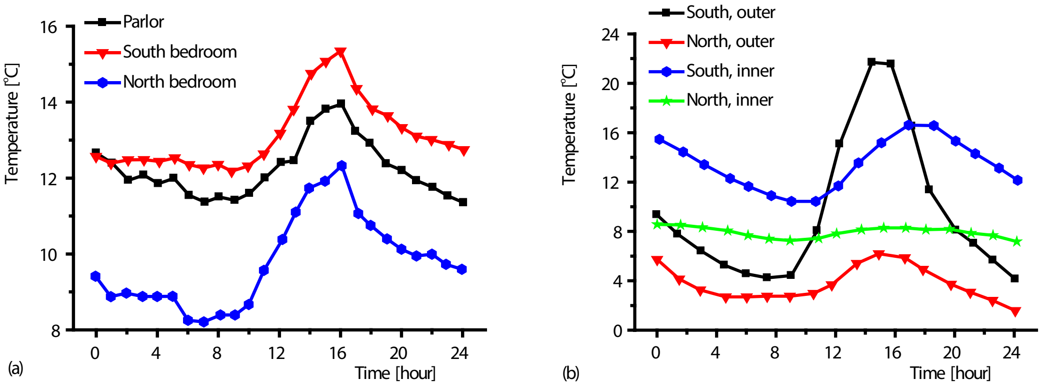

Figure 3. Variation of internal and external surface temperatures of different rooms and north and south walls; (a) shows the temperature changes in different rooms, (b) shows the change of the internal and external surface temperatures of the north and south walls

Test results of indoor and outdoor thermal environment of phase change energy storage building

The change of indoor temperature of Lhasa on winter solstice and that of residence with phase change energy storage wall heat transfer model are compared. It can be observed from fig. 4(a) that the variation trend of outdoor horizontal surface, east wall, west wall, south wall, north wall, and air temperature is basically the same on the winter solstice day, and the average temperature is 0.64 °C, 1.59 °C, 0.75 °C, 3.18 °C, 0.37 °C, and 1.59 °C, respectively, among which the average temperature of the south wall is the highest. As can be observed from fig. 4(b), the indoor temperature of residences with phase change energy storage wall heat transfer model is the lowest around 9:00, which is 11.38 °C. The temperature reaches a peak at around 17:00, that is, 25.33 °C, and the temperature difference is 13.95 °C. As can be observed from fig. 4(c), the surface temperatures of the indoor walls of the residences with the phase change energy storage wall heat transfer model are not very different, among which the average temperatures of the indoor east wall, west wall, south wall, north wall and air are, respectively 16.62 °C, 16.56 °C, 16.75 °C, 16.52 °C, and 17.25 °C.

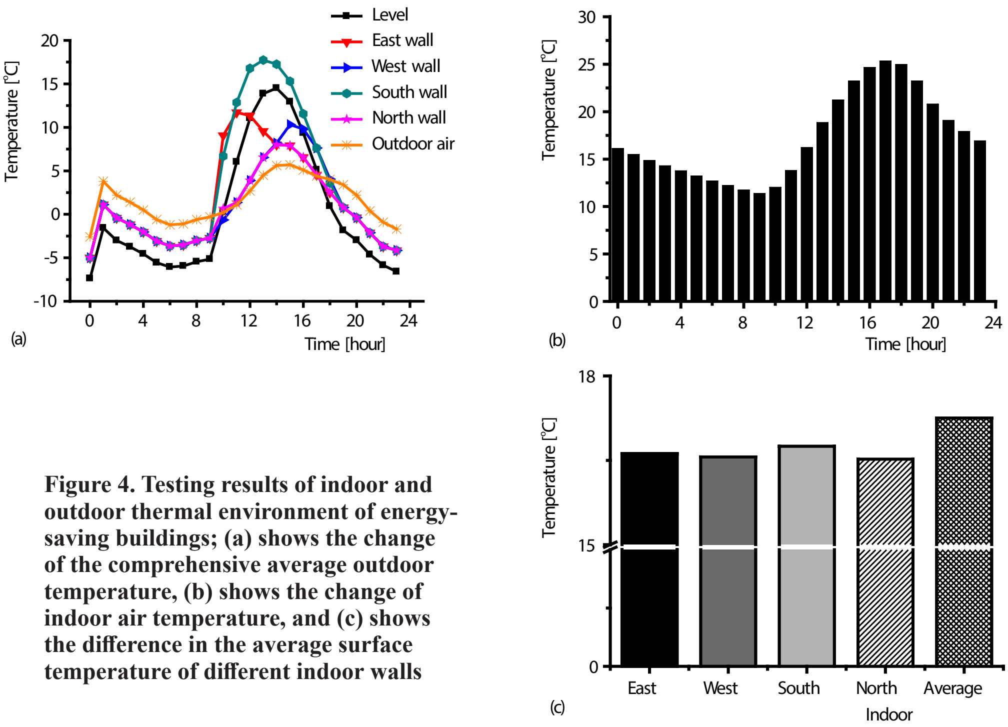

Figure 4. Testing results of indoor and outdoor thermal environment of energy-saving buildings; (a) shows the change of the comprehensive average outdoor temperature, (b) shows the change of indoor air temperature, and (c) shows the difference in the average surface temperature of different indoor walls

Discussion

In this study, it is found that the indoor temperature difference between the north bedroom and the south bedroom in a residential house in Lhasa is 3.3 °C, and the temperature of the south bedroom is higher than that of the north bedroom because the south bedroom faces the sun. It can be observed that solar radiation has an important contribution the thermal stability of the room. The main heat sources in the room are all from the passive heat collection of single glass external windows in the south direction. However, the temperature variation in different time periods is quite different, which indicates that the indoor thermal environment still needs to be further improved. Through the indoor and outdoor thermal environment test in Lhasa, it can be concluded that the solar radiation in this area contributes a lot to the indoor thermal environment, but there are still large indoor temperature differences and other problems. Therefore, it is necessary to build an envelope enclosure for thermal energy storage to maintain and improve the stability of the indoor thermal environment. By analyzing the outdoor integrated temperature of different orientations, it can be found that the outdoor integrated temperature of the south wall fluctuates greatly, and the outdoor integrated temperature of the north wall fluctuates least. Zhang et al. analyzed the heat transfer process of building envelope in Shanghai area in summer, and found that the cooling rate of exterior wall surface in the south direction was lower than that of other orients, indicating that the solar absorption rate of southern wall was higher [13].

The PCM is a kind of latent heat storage material. Because of its ability to absorb and release latent heat, PCM is often used to improve the thermal performance of buildings. Kharbouch *et al*. [14] applied PCM to enhance the thermal performance of building envelope, and found that the application of PCM to wall or roof could increase the indoor thermal performance, and the effect of applying PCM on the inner side of the wall is more obvious. Therefore, in this study, the PCM is applied on the inside of the wall (close to the interior) for subsequent research. The PCM is used to build an energy storage wall model for passive solar energy buildings, and indoor temperature of residential buildings is simulated with the temperature data of the winter solstice in Lhasa area. The results show that all the indoor temperatures are kept above 10 °C. Chen *et al*. [15] found that the application of PCM to the north wall of solar greenhouse increased the heat storage capacity of the wall by 35.27-47.89%, and increased the effective accumulated temperature by 1.58-4.16 °C. This is basically consistent with the research results that the original room temperature of the living room is 12.2 °C, and the indoor temperature increases by 5.05 °C after PCM is used to build the energy storage wall. Lee *et al*. [16] applied PCM to residential walls in the east, west, south, and north directions and evaluated their thermal performance. The results showed that the average daily heat flux of different walls decreased by 25.4%. While in this study, it is found that the average temperature inside the original indoor south wall is 13.4 °C, and the average temperature inside the north wall is 7.9 °C. When PCM is applied to passive solar buildings, the average temperature of the inner surface of the south wall and the north wall is 16.75 °C and 16.52 °C, respectively, increasing by 25.0% and 109.1%.

Conclusion

In this study, taking Lhasa with high sunshine as the research object, the indoor and outdoor thermal environment differences of residential buildings in Lhasa in winter are evaluated. Then, a phase change energy storage wall is constructed based on passive solar energy building, and the changes of interior surface temperature and indoor air temperature of different walls are analyzed during the winter solstice. The results show that the radiation intensity of direct solar radiation in Lhasa in winter accounts for 67.6% of the total radiation intensity, belonging to the area with high sunshine. The temperature difference between day and night in winter is large and dry, and the temperature in the south direction is higher than that in the north direction. After building a phase change energy storage wall and simulation with data of winter solstice day in Lhasa, it is found that the average indoor temperature can reach 17.25 °C, and the temperature difference between the inner surface of different walls is not big. However, there are still deficiencies in this study. For example, the influence of the change of thermal parameters of PCM on the indoor thermal environment is not analyzed, and further studies in this direction can be carried out. In conclusion, the application of phase change energy storage wall in passive solar residential buildings in Lhasa can effectively improve the indoor thermal environment.

References

[1] Ren, Y. H., *et al*., Research on the Evaluation Model and Suggestions of Coal Resources Mining Level in China, *IOP Conference Series Earth and Environmental Science*, *170* (2018), 2, 022064
[2] Li, M., *et al*., Response of Energy Consumption for Building Heating to Climatic Change and Variability in Tianjin City, China, *Meteorological Applications*, *23* (2016), 1, pp. 123-131
[3] Shaofei, W., Construction of Visual 3-D Fabric Reinforced Composite Thermal Performance Prediction System, *Thermal Science*, *23* (2019), 5, pp. 2857-2865
[4] Kwon, H. J., *et al*., Evaluation of Building Energy Saving through the Development of Venetian Blinds' Optimal Control Algorithm According to the Orientation and Window-to-Wall Ratio, *International Journal of Thermophysics*, *39* (2018), 2, 30

[5] Castaldo, V. L., *et al*., How Outdoor Microclimate Mitigation Affects Building Thermal-Energy Performance: A New Design-Stage Method for Energy Saving in Residential Near-Zero Energy Settlements in Italy, *Renewable Energy*, *127* (2018), Nov., pp. 920-935
[6] La Fleur, L., *et al*., Measured and Predicted Energy Use and Indoor Climate before and after a Major Renovation of an Apartment Building in Sweden, Energy and Buildings, *146* (2017), July, pp. 98-110
[7] Toleikyte, A., *et al.*, Cost Curves of Energy Efficiency Investments in Buildings – Methodologies and a Case Study of Lithuania, *Energy Policy*, *115* (2018), Apr., pp. 148-157
[8] Shaofei, W., *et al*., Research on Internet Information Mining Based on Agent Algorithm, Future Generation Computer Systems, *86* (2018), Sept., pp. 598-602
[9] Hongwei, W., *et al*., Energy Saving Reconstruction and Suitability Analysis of Teaching Building Envelope in Severe Cold Area, *Journal of Shenyang Jianzhu University (Natural Science)*, *33* (2017), 3, pp. 497-505
[10] Zhou, Y., Wang, S., Application Effect of Composite Phase Change Energy Storage Thermal Insulation Mortar in Solar Greenhouse, *Transactions of the Chinese Society of Agricultural Engineering*, *33* (2017), 20, pp. 190-196
[11] Liu, C., *et al*., Investigations on Thermal and Optical Performances of a Glazing Roof with PCM Layer, *International Journal of Energy Research*, *41* (2017), 14, 2
[12] Liu, X., *et al.*, Numerical Study on Cooling Performance of a Ventilated Trombe Wall with Phase Change Materials, *Building Simulation*, *11* (2018), 7, pp. 1-18
[13] Hongying, Z., *et al*., The Effect of Solar Absorption Coeficient on Net Heat Gain of Building Envelopes in Summer, *Acta Energiae Solaris Sinica*, *38* (2017), 1, pp. 156-163
[14] Kharbouch, Y., *et al*., Thermal Performance Investigation of a PCM-Enhanced Wall/Roof in Northern Morocco, *Building Simulation*, *11* (2018), 6, pp. 1-11
[15] Chen, C., *et al*., Thermal Performance of an Active-Passive Ventilation Wall with Phase Change Material in Solar Greenhouses, *Applied Energy-Barking Then Oxford*, *216* (2018), 1, pp. 602-612
[16] Lee, K. O., *et al*., Thermal Performance of Phase Change Materials PCM-Enhanced Cellulose Insulation in Passive Solar Residential Building Walls, *Solar Energy*, *163* (2018), Mar., pp. 113-121

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