ANALYSIS OF THERMAL CHARACTERISTICS AND THERMAL STORAGE PERFORMANCE OF ENERGY-SAVING PHASE CHANGE THERMAL STORAGE MATERIALS IN BUILDINGS

by

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In order to explore the thermal characteristics and thermal storage performance analysis of energy-saving phase change heat storage materials in buildings, taking the common exterior wall insulation composite wall structure in southwestern China as an example, the influence of insulation board structure thickness design on the total cost of residential air conditioning energy consumption and insulation board cost is studied, thus clarifying the concept and calculation origin of economic insulation thickness. The experimental results show that by drawing mathematical functions of energy consumption cost, total cost, and insulation material cost in the same 2-D co-ordinate, it is intuitively demonstrated that the minimization of total cost can be ensured when the insulation thickness is in an economic state, and the specific economic thickness can be accurately calculated through example data. Therefore, specific measures for improving external wall insulation from refined insulation structure design are proposed. It has been proven that the design of the exterior wall insulation layer structure is an important way to improve the overall energy-saving benefits of building exterior wall insulation.

Key words: *phase change heat storage material, heat storage characteristics, heat storage properties, consumption cost*

Introduction

Since the beginning of the 20th century, the growth rate of human energy consumption has greatly exceeded the growth of population. In the first 75 years of the 20th century, the world population has increased by 1.5 times, while energy consumption has skyrocketed by 10 times, if growth continues at this rate, there will inevitably be energy depletion worldwide. Moreover, the uncontrolled exploitation and unreasonable use of fossil fuels have also caused serious air and water pollution, resulting in various environmental issues such as SO_x, NO, and global warming. Therefore, energy issues have become a major issue for human society and global sustainable development [1].

The human demand for architecture has gone through four stages: shelter, comfortable building, healthy building, and green building. The first stage is low or even zero energy consumption, the second and third stages are high energy consumption, and the fourth stage is high energy efficiency, extensive use of renewable energy, unused energy, and being close to nature and protecting the environment. In developed countries, building energy consumption accounts for approximately 30-40% of total energy consumption [2].

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China is an energy scarce country. In terms of energy application, as an important material foundation of the national economy, electricity has been vigorously developed through the efforts of several generations, especially the implementation of the *multi household electricity* policy in the late 1980's. At present, China's power generation and installed capacity have ranked second in the world. However, China's power supply is still very tight. In 2005, there was a phenomenon of power shortage in multiple provinces in China, especially with a large peak valley difference in the power supply system. For example, the maximum peak valley difference of the Northeast Power Grid is already 37% of the maximum load, while the North China Power Grid has reached 40%. During peak periods, there is a severe shortage of electricity, which requires power cuts and restrictions, while during low periods, small loads result in a large amount of electricity being wasted on the power grid. In order to address this issue, the country introduced the *Peak Valley Electricity Price Policy* in 1994 and *The 1995-2000 Electricity Saving Plan*, which clearly stated that *saving peak electricity will be an important part of alleviating the contradiction of power shortage*. The goal of shifting peak electricity consumption 10-12 million kW by 2000 was proposed to alleviate the current contradiction. In order to encourage users to level off their peak electricity consumption, power departments in various provinces, cities, and regions have announced electricity policies and peak valley time of use electricity prices, using economic means to promote the realization of *shifting peak to valley* electricity. For example, the North China Power Grid has announced the implementation of time of use electricity prices, which have a peak valley difference of nearly five times. The application of phase change energy storage technology can fully utilize the policy of *shifting peak to valley* electricity, utilize the price difference between peak and valley electricity, and store heat and cold in buildings during low power periods, thereby achieving the goal of energy conservation.

In recent years, a hot topic in the research of phase change and chemical reaction energy storage has been its application in the fields of building energy conservation and HVAC. On the one hand, this is due to the fact that the construction industry is a crucial industry in various countries around the world, and its technological progress will generate significant economic and social benefits. On the other hand, it is due to the increasing emphasis on environmental protection and energy conservation, as well as the economic drive generated by the day and night electricity pricing system. The International Energy Agency (IEA) project team, energy conservation through energy storage (ECES), discussed and confirmed the launch of Annex 10 (with the theme of *phase change and chemical reaction heat storage*) in 1999, which lasted for three years [3]. The application of phase change and chemical reaction heat storage in buildings is also listed as the main research direction. In the field of HVAC, due to the increasing demand for comfort in indoor environments, the corresponding building energy consumption has also increased, resulting in rapid energy consumption and intensified environmental pollution. The combination of phase change energy storage materials with building structures provides an effective way to improve building comfort, reduce energy consumption, and improve negative environmental impacts.

Adding basic components such as phase change energy storage wall panels to the building envelope structure cannot only improve the thermal comfort of the room, reduce and shift the load of air conditioning and heating, but also reduce the frequency of opening air conditioning and heating equipment, truly achieving the goal of energy conservation. The application research of phase change energy storage theory and technology in the fields of building energy conservation and HVAC involves multiple disciplines such as architecture, materials, engineering thermophysics, HVAC, and belongs to interdisciplinary issues, studying the theory and technology of phase change energy storage to create a hygienic, comfortable, and energy-saving building environment has become a hot topic of concern. It has significant scientific significance and practical value for building energy conservation and sustainable development, laying a theoretical foundation and technical guidance for China's high comfort and low energy buildings.

Literature review

With the increasing energy consumption in buildings and the increasing demand for indoor thermal comfort, the research on phase change heat storage technology in building energy conservation has received widespread attention. By driving changes in the physical state of PCM through changes in environmental temperature, building temperature regulation or auxiliary heat storage can be achieved, thereby alleviating the contradiction of mismatched energy consumption in time and space in buildings. Paraffin wax has the advantages of being less prone to supercooling and phase separation, low corrosiveness and toxicity, stable performance, and low cost, making it widely used in buildings. However, due to its poor thermal conductivity, it may lead to untimely and insufficient heat storage/release when combined with enclosure structures, reducing the utilization rate of latent heat. By designing a phase change heat storage component, fig. 1, for the inner surface of the wall, using metal aluminum as the packaging material for paraffin wax and the material for internal heat transfer strengthening ribs, the packaging problem is solved while improving the thermal conductivity of paraffin wax. Compared to the fixed PCM wall, it has a higher energy storage density and does not need to consider the impact of heat transfer strengthening materials on the latent heat, durability, and other aspects of the phase change material, and it has many advantages in preparation, installation, and performance.

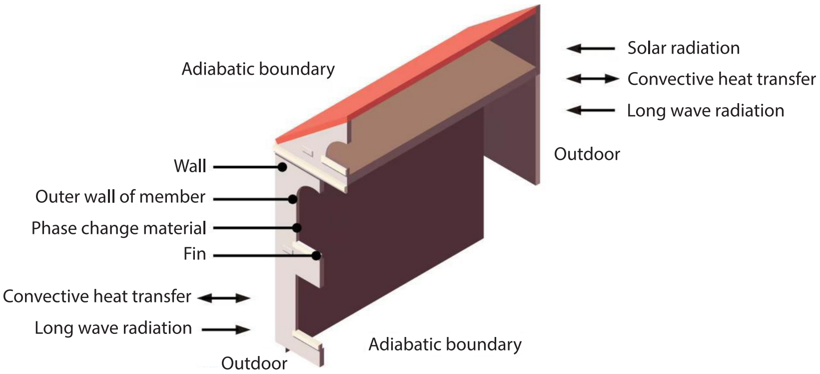

Figure 1. Physical model of composite wall of phase change heat storage member

To improve the performance of phase change thermal storage systems, Cui *et al.* [4] proposed a novel method of adding TiO_2 nanoparticles, metal foam, and ultrasonic fields to investigate their synergistic effects on the enhancement of conduction and convection heat transfer. The thermal characteristics of the TES system, including the TES time distribution and power consumption, are discussed to evaluate the effects of TiO_2 nanoparticles and the ultrasonic field on the TES rate and TES efficiency. The results show that when the pressure of TiO_2 nanoparticles is 5.0 wt.% and the ultrasonic power is 100 W, the short-term TES capacity reaches 46.50, while the TES efficiency decreases to 10.66. Kiyokawa *et al.* [5] attempted to measure the rotational energy of TES using tetrabutylammonium acrylate (TBAc) hydrate as a phase change material. Adding mechanical agitation or ultrasonic vibration separate the adhesive from the hydrates in the heating system increases thermal resistance. The impact of external forces is also evaluated by changing their rotation and frequency. Teja *et al.* [6] analysis of the influence of Al_2O_3 nanoparticles volume fraction (0, 2, 5) on paraffinic PCM and alcohol on the heater function (bottom and side walls) of a 2-D square thermal energy storage machine. Thermal changes at 500 seconds, 1000 seconds, and 3000 seconds were investigated in ANSYS FLUENT R18.1. The solidification and melting behavior of nanoPCM were investigated under laminar flow conditions using the enthalpy pore model. We created an independent rating network and selected 115538 of the best products. The results show that the addition of nanoparticles to PCM can improve its thermal properties.

The author's main research direction is building exterior wall insulation and energy conservation. After fully introducing the research background at home and abroad, the current domestic research overview, and the concept and practice classification of exterior wall insulation systems, based on certain research theories, taking the common exterior wall insulation composite wall structure in southwestern China as an example, this study investigates the impact of insulation board structure thickness design on the total cost of residential air conditioning energy consumption and insulation board cost, in order to clarify the concept and calculation origin of economic insulation thickness, and then propose targeted ways to improve the energy-saving performance of building exterior wall insulation.

Theoretical basis for research

The following is the theoretical basis for the impact of insulation layer structure design on the energy-saving of building exterior wall insulation: Related experiments have found that there is an inherent mathematical relationship between the total cost of achieving a certain level of comfort in building exterior wall insulation and energy conservation, as well as the thickness and performance of insulation materials, as well as the cost of air conditioning consumption maintain a certain level of indoor comfort [7]. Among these factors that have an inherent relationship, there is a thickness of insulation materials, we call it economic insulation thickness, which not only ensures the insulation and comfort of the indoor environment, but also minimizes the total cost of achieving this goal. The specific mathematical calculation model for this economic insulation thickness:

$$Q_\mathrm{t} = Q_\mathrm{w} + Q_\mathrm{s} \tag{1}$$

$$Q_\mathrm{w} = \frac{k \times HDD18 \times 86400}{3600 \times 1000} \tag{2}$$

$$Q_\mathrm{s} = \frac{k \times CDD26 \times 86400}{3600 \times 1000} \tag{3}$$

where Q_t [kWhm^{-2}] is the uses a simplified algorithm to calculate the annual total building heat transfer load based on the number of air conditioning days and heating days, taking into account only the impact of the final heat dissipation loss transmitted through the enclosure structure on the thickness of the insulation material, Q_w [kWhm^{-2}] – the winter load, Q_s [kWhm^{-2}] – the summer load, *HDD*18 and *CDD*26 [°C per day] are heating degree days and air conditioning degree days, respectively. The value of k [Wm^{-2}K^{-1}] is the heat transfer coefficient of the building's exterior wall, expressed in. The calculation formula for k:

$$k = \frac{1}{R} = \frac{1}{R_\mathrm{i} + R_\mathrm{w} + R_\mathrm{in} + R_0} \tag{4}$$

where R_i is the heat transfer resistance of the inner surface of the exterior wall, which can be queried through design specifications, R_0 – the heat transfer resistance of the external surface of the exterior wall, which can be queried through design specifications [8], R_in [m^{2}KW^{-1}] – the thermal resistance of the insulation material, and R_w – the thermal resistance of the base wall. The calculation formula for R_in:

$$R_\text{in} = \frac{\delta}{\lambda} \tag{5}$$

where λ [Wm^{-1}K^{-1}] is the indicates the thermal conductivity of the insulation material it self and δ [m] – the thickness of insulation material.

The cost calculation formula for external wall insulation consumption:

$$C_\text{w} = \frac{Q_\text{w}}{COP} C_\text{e} \tag{6}$$

$$C_\text{s} = \frac{Q_s}{EER} C_\text{e} \tag{7}$$

where C_w is the cost of using air conditioning in the winter of the year, C_s – the cost of using air conditioning in the summer of the year, both in Yuan per m^2, COP – the heat efficiency ratio of air conditioning systems, EER – the energy efficiency ratio of air conditioning refrigeration, and C_e [Yuan per kWh] – the electricity price. Considering the impact of inflation, the air conditioning cost is discounted to the current current current value using the present value coefficient method. The calculation formula:

$$PWT = \frac{1 - \left(1 + I^*\right)^{-N}}{I} \tag{8}$$

$$I^* = \frac{I - g}{I + g}, \ \ (g < I) \tag{9}$$

$$I^* = \frac{I - g}{I + I}, \ \ (g > I) \tag{10}$$

where PWF is the present value coefficient, g – the inflation rate, I – the loan interest rate, and N [year] – the life cycle of the insulation material.

Therefore, the calculation formula for the total cost of external wall insulation composed of insulation material costs and energy consumption costs for air conditioning:

$$C_\text{t} = \left(C_\text{w} + C_\text{s}\right) \times PWF + \delta \times C_\text{in} = \frac{0.024 \times PWF \times C}{\left(R_\text{wt} + \dfrac{\delta}{\lambda}\right)} \times \left(\frac{HDD}{COP} + \frac{CDD}{EER}\right) + \delta \times C_\text{in} \tag{11}$$

$$R_\text{wt} = R_\text{i} + R_0 + R_\text{w} \tag{12}$$

where C_in is the selling price of insulation materials, expressed in Yuan per m^3 and R_wt [m^{2}KW^{-1}] – the total thermal resistance of the building's exterior wall without insulation materials. The derivative of eq. (11) is taken:

$$\frac{\mathrm{d}C_\text{total}}{\mathrm{d}\delta} = 0$$

the obtained δ economic insulation thickness mentioned previously is expressed mathematically:

$$\delta_{\mathrm{op}} = \sqrt{0.024 \times PWF \times \left(\frac{HDD}{COP} + \frac{CDD}{EER}\right) \times \lambda \times c_{\mathrm{e}} - R_{\mathrm{wt}} \times \lambda} \tag{13}$$

According to the mathematical function model, the mathematical function graphics of energy consumption cost, total cost, and insulation material cost are plotted in the same 2-D co-ordinate, as shown in fig. 2. From this, the value range of economic insulation material thickness can be intuitively seen [9]. The most economical thickness value can be accurately calculated using the aforementioned formula in the example, and specific examples are provided in fig. 2.

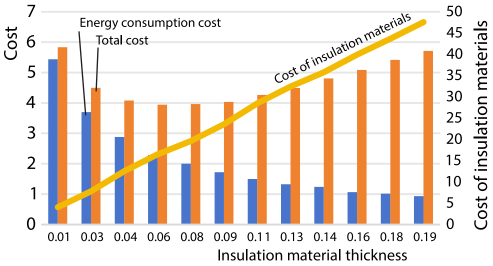

Figure 2. Thickness and cost relationship diagram of economic thermal insulation materials

Case studies

As previously mentioned, we can establish and study a mathematical model to minimize the total cost of air conditioning energy consumption and insulation material costs while maintaining a certain comfortable indoor temperature. At this point, the insulation material thickness is called the economic insulation thickness. Next, the author takes the composite wall structure commonly used in buildings in southwestern China as an example to conduct a specific case study [10]. It is found that due to its high cost benefit, it is the commonly used thermal insulation material in the energy-saving structure of the building exterior wall in southwest China. For example, the economic insulation thickness of cement mortar, reinforced concrete wall, energy-saving phase change heat storage material foam board and gypsum mortar composite wall structure is calculated as an example. Based on the theoretical basis introduced by the previous author, we assume that the selling price of energy-saving phase change heat storage materials in the market is 400 Yuan per m^3, and as insulation materials, they have a lifespan of 20 years. The inflation rate in 2019 was 4.8%, and the loan interest rate was 7.65%, resulting in a PWF of 15.42.

Assuming that local residents in the southwest region use heat pump air conditioning and the air conditioning is in operation all day, $CDD26$ and $HDD18$ are 241 °C per day and 1073 °C per day, respectively, with a COD value of 3.0, EER of 2.6, R_{i} of 0.11 m^{2}K/W, $R0$ of 0.05 m^{2}K/W, and C_{e} of 0.52 Yuan per kWh, according to eq. (11) in the previous theoretical introduction, the total cost can be calculated.

According to the relevant parameters and values of the wall structure type in tab. 1, and according to the mathematical function obtained in the previous theoretical basis introduction, the energy consumption cost, total cost, and insulation material cost can be calculated in the same 2-D co-ordinate to obtain the relationship between the total cost and insulation material thickness in fig. 3.

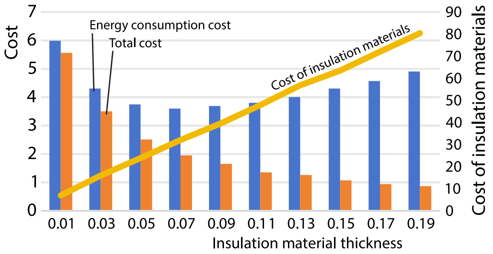

Figure 3. The relationship between the total cost and the thickness of the insulation materials

Table 1. Comparison of Nusselt numbers

Wall type	Simplified combination of composite wall structure	Thickness [mm]	Thermal resistance value [m^2KW^{-1}]	Thermal conductivity [$Wm^{-1}K^{-1}$]	The heat transfer coefficient [m^2KW^{-1}]
Phase change heat storage material heat preservation wall	Cement mortar	20	0.02	0.93	1.17
	Reinforced concrete wall	200	0.11	1.74	
	Phase change thermal storage materials	30	0.71	0.04	
	Plastering adhesive	5	0.01	0.93	

As shown in fig. 3, as the thickness of the insulation material increases, the price of heat insulation material increases linearly, while the energy consumption of cold air decreases. After reaching a certain level, the rate of decrease in energy consumption of the air conditioner is generally uniform, but the total cost curve quickly decreases to a minimum value and then shifts to an increase. As can be seen from the figure, the total value reaches the minimum value when the thickness of the insulation layer on the outer wall of the building is 80 mm. Therefore, in the aforementioned situation, it can be seen that the thickness of commercial insulation is 80 mm.

The previous conclusion is calculated under the condition that both summer cooling and winter heating of air conditioning are operating throughout the day. Due to the fact that in real life, the intensity of air conditioning usage is far from reaching this level, the following calculation is based on the air conditioning working for 8 hours per day, and the mathematical function obtained from the previous theoretical basis introduction is also used, by combining the energy consumption cost, total cost, and insulation material cost in the same 2-D co-ordinate, fig. 4 can be obtained [11]. It can be seen that, with other parameters unchanged, if the air conditioning is changed to work eight hours a day, the economic insulation thickness of the region is 40 mm.

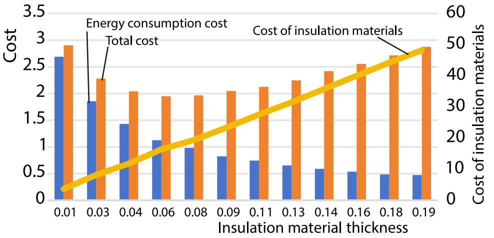

Figure 4. Relationship between the total cost and the thickness of the thermal insulation materials

In the calculation process of the aforementioned example, it can be seen that thickening the insulation layer thickness is one of the effective ways to resist the total heat loss of buildings. However, in daily use, based on the relationship between the total cost of energy consumption and building insulation costs and the thickness of insulation boards, it can be seen that in the economic insulation thickness, the value of building external wall insulation energy conservation can be maximized when the total cost is minimized. Therefore, the design of external wall insulation layer structure is an important way to improve the overall energy-saving benefits of building external wall insulation [12].

Research has found that different materials have different thermal conductivity, density, and combustion performance. The size of the vertical stress area affects the compressive strength of the material. The thickness of insulation materials directly affects the insulation effect. The construction ratio of materials affects the comprehensive performance and lifespan of the structural layer. Therefore, in order to ensure the strength, performance coefficient, and overall quality of external wall insulation of the materials themselves, it is necessary to pay attention the selection of insulation materials, the structural design of insulation layers, and the construction ratio of building materials. Therefore, the optimal values and combinations of various structural design parameters can be ensured from three aspects: refined structural design, selection of excellent insulation and energy-saving materials, and improvement of construction technology. Due to the application of energy-saving phase change heat storage materials in building insulation walls in southwestern China, the author mainly focuses on the economic structural thickness of insulation materials [13]. Therefore, the author will then propose specific implementation methods to improve the energy-saving performance of building exterior wall insulation through refined structural design:

- Develop and continuously optimize and update existing structural design standards.
- Select insulation layer structure design scheme according to local conditions.
- Improve and refine the design elements of various insulation layer structures.
- Strictly monitor the construction phase to minimize the impact of construction on the insulation layer.
- Learn and introduce excellent structural design ideas and principles.
- Increase the training of structural design personnel from both theoretical and practical perspectives [14].

Conclusion

The author takes the research on energy conservation of building exterior wall insulation as the main direction, and based on the application of energy-saving phase change heat storage materials in building walls, studies the influence of insulation material thickness on the energy-saving performance of exterior wall insulation through mathematical theoretical models. By drawing mathematical function graphs of energy consumption cost, total cost, and insulation material cost in the same 2-D co-ordinate, the author intuitively demonstrates that the minimization of total cost can be ensured when the economic insulation thickness is in place, and the specific economic thickness can be accurately calculated through example data, thus proposing specific measures to improve external wall insulation from refined insulation structure design. I hope the author's research can provide some guidance for the design of exterior wall insulation structures or improvement ideas for building exterior wall insulation energy conservation in practice.

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