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Research on the indoor temperature regulation characteristics of a nearly zero energy building with the nonlinear heat capacity building components: A simple model

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ABSTRACT

With establishment of global carbon reduction targets, energy conservation and emission reduction of building is imperative. By passive building design method, nearly zero energy buildings (nZEB) can decrease building energy consumption requirements. To reduce indoor temperature fluctuation of the nZEB in heating season, the conventional energy storage materials (CESM) or phase change materials (PCM) are utilized in the building components for thermal storage. The heat capacity of the PCM was simplified as ideal nonlinear heat capacity. To reveal the indoor temperature distribution characteristic in the nZEB affected by the building components with or without the nonlinear heat capacity, a simplified mathematical model was established. Several evaluation indicators were put forward to describe indoor temperature regulation difference between the CESM and the PCM. The results show that indoor temperature distribution characteristics of the nZEB with PCM was significantly different with that of the CESM building. The maximum indoor temperature distribution frequency of the PCM building is much larger than that of the CESM building. The maximum indoor temperature distribution frequency of PCM building was more concentrated and occurred close to the phase transition temperature. The maximum indoor temperature distribution frequency of the CESM is not exceed 10%, however, that of the PCM building can reach 42% in the same work condition. The maximum indoor temperature distribution frequency, the indoor comfort guarantee ratio and the latent heat utilization time ratio of the PCM building can be obviously increased by selecting the phase transition temperature close to the average indoor temperature in the heating season. The study work represent that the PCM building components with the nonlinear heat capacity can regulate the indoor temperature distribution frequency by change phase transition temperature.

Keywords: Phase change material; Nearly zero energy buildings; Thermal storage; Indoor environment

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Nomenclature

Symbols

L	length,m
W	width,m
H	height,m
V	volume,m ³
F	area,m ²
U	Overall heat transfer coefficient,W/(m ² K)
V	volume,m ³
N	Ventilation frequency, air change/h
T	temperature, K
Q	heat transfer rate,W/m ²
m	quality,kg
P	frequency distribution
t	time,s
ρ	density, kg/m ³
c	specific heat, J/kg K
h	convection heat transfer coefficient,W/(m ² K)

Subscripts

w	wall
i	integer
a	air
win	window
in	indoor
out	outdoor

Abbreviations

nZEB Nearly Zero Energy Buildings

PCM phase change material

CESM conventional energy storage material

1. Introduction

Building energy consumption accounts for about 40% of total energy consumption in the world, and it is predicted that global building energy consumption will rise to 50% of total energy consumption by 2050[1,2]. With global energy shortage, countries have accelerated process of energy conservation and emission reduction task, and the near zero energy building (nZEB) has gradually become the development direction of buildings[3,4]. nZEB refer to the building with high energy performance and low energy required, and renewable energy should be responsible for most of the energy consumption [5]. It was considered as an effective solution for energy conservation and emission reduction in the field of buildings. And the application of composite phase change materials(PCM) in the building envelope has become the focus of attention in the field of nZEB [6–8].

Due to nZEB having well insulation effect and inherent heat storage capacity, the heating or cooling scheme is obviously different from the traditional building. Liu et al. [9] tested in a nZEB over two years found that it reduced heating and cooling requirements by 55.2% and 54.0% compared with traditional buildings, respectively. It shows that nZEB can provide a comfortable indoor temperature with less energy consumption. Dr´eau et al. [10] compared the difference between the poorly insulated and well insulated buildings, with different heating and heat storage schemes. The results show that well insulated building with higher heat capacity were more suitable for long term temperature regulation, and it could stop heating over 24h under the condition of keeping indoor temperature comfortably. Bai et al. [11] established a mathematical model of lightweight passive buildings. They analyzed the

factors affecting the heat storage process of the PCM envelope in lightweight passive buildings in summer. Then the relationship between the performance of PCM and outdoor temperature in passive buildings was compared.

PCM have the characteristics of nonlinear heat capacity and high energy storage density, and have the effect of heat storage and indoor temperature regulation in buildings. Therefore researchers have carried out a lot of work on the application effect of PCM building components in the thermal environment of nZEB [12–17].

Mahdaoui et al. [18] proposed the integration of PCM in architectural hollow bricks (widely used in Moroccan buildings) to improve the thermal performance of external walls and evaluated the thermal effect of weather conditions of this building. The results of the study show that the building bricks with PCM can stabilize and reduce indoor temperature fluctuations. A study by Mohseni et al. [19] came to a similar conclusion that wall materials integrated with PCM could improve indoor comfort and reduce indoor temperature fluctuations. Gupta et al. [20] studied the regulation effect of indoor temperature by latent heat storage brick. The results show that the latent heat storage brick can reduce the average indoor peak temperature under the cooling condition, and the time lag is 180 min. Kumar et al. [21] studied the effectiveness of gypsum plaster loaded with phase change material in regulating indoor temperature of the building, the experiment shown that it has superior thermal reliability, and suitable for regulate indoor temperature. Hou et al. [22] proposed a heat transfer model for lightweight building walls integrated with PCM. The authors verified that the wall of the building with the PCM in the middle is better than the traditional wall when the phase transition temperature is suitable. Zhang et al. [23] studied the effect of different PCM thermal performance of the latent heat thermal storage wallboard in residential buildings. The results show that applying the PCM to internal wall of the solar building has a great effect of energy efficiency and indoor comfort.

In order to study the influence of building components performance parameters on indoor thermal environment, simulation calculation methods are commonly used in many researches [24–26]. While current technologies can make simulation calculation precise, but always too complex to need much time. But in the application of engineering applications, there are always do not need for calculations too complicated. Therefore, simplified building simulation model may be more valuable than complex model in certain situations [27]. Zeng et al. [28] studied the optimal form of nonlinear specific heat capacity inside building by establishing a simplified model of two plate room model in passive building, aiming at improving indoor thermal comfort. Then N-segment method is proposed to approximate the nonlinear specific heat capacity. The results show that this method can effectively solve the nonlinear ideal specific heat capacity inside buildings. Bagheri et al. [29] used thermal networks and system identification approach to simulate the indoor air temperature of buildings. The results show that the simplified model can well predict the indoor temperature in the next week. Lu et al. [30] proposed that temperature elastic coefficient was used to calculate the heat transfer process between the external wall and the air in the room, and effective thermal capacity was used to calculate the thermal mass. The results show that the wall thermal resistance, window-wall ratio, air exchange rate and thermal insulation position all affect the temperature elastic coefficient and effective thermal capacity.

The nZEB has excellent insulation performance, and the heat capacity of PCM has a characteristic of non-linear variation. For the simulation study the indoor thermal environment of nZEB, the simulation model currently used has the problems of too complex and need too long time [31]. This paper in order to quickly calculate the indoor temperature regulation effect of energy storage materials with nonlinear heat capacity in nZEB, a simplified mathematical model was established. Then the difference of indoor temperature regulation effect of PCM and CESM were compared in nZEB. The indoor temperature regulation effect of building components with nonlinear heat capacity is analyzed by statistical method. The aim is to brought forward a method to quickly obtain the indoor temperature regulation effect of nonlinear heat capacity building components by simplified mathematical model.

2. Methodology

2.1. Physical description of nZEB with PCM

Building indoor temperature is influenced by outdoor environment, indoor heat, ventilation and air exchange, building envelope performance, and operation mode. Building envelop with high heat capacity can reduce the indoor temperature fluctuation. If PCM is mixed into the building envelope, the thermal storage capacity of building

envelope can be significantly increased. The effects of exterior and internal building envelope's heat capacity on indoor thermal environment would be different. For lightweight building exterior envelope structure with small heat capacity, the effect of building external wall's heat capacity on indoor environment can be neglected, while the focus of the analysis is on the influence of building internal envelope's heat capacity.

In this study, a typical room of nZEB was selected as the case for analysis indoor temperature regulation effect by the building components with PCM and CESM. The difference between the room with PCM and the room with CESM would only in the thermal performance of energy storage materials. The simplified room model in the case is shown in Fig. 1. And the simplified model of building thermal process is shown in Fig. 2.

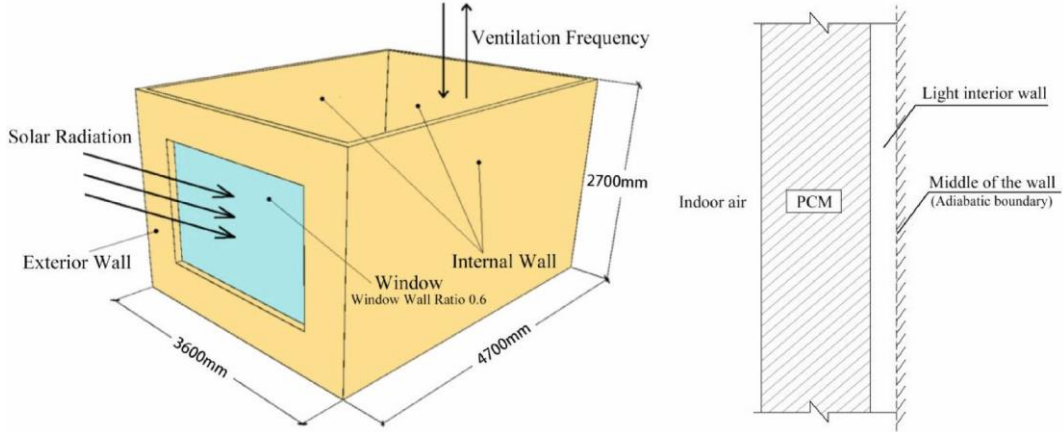


Fig. 1. The simplified room model in the case.

Nearly zero energy buildings have high requirements for thermal performance of buildings, technical standard for nearly zero energy buildings was released by China in 2019 [32]. The standard requires that in cold areas of China, the heat transfer coefficient of the envelope of nZEB should be between 0.15 and 0.2W/(m²K), the heat transfer coefficient of the window should be less than 1.2W/(m²K), and the ventilation frequency should be less than 0.6/h. According to the requirements of this standard, the physical structure parameters and operating conditions of the building is shown in Table 1.

The surface heat convection coefficient (h_{co}) is the key factor to calculate the heat transfer of the building. In the building, the inner surface of the envelope can be considered as natural convection, the formula of natural convection of heat transfer can be described by Eq (1):

$$Nu=C(Gr \cdot Pr)^n \quad (1)$$

Alamdari and Hammond [33] analyzed the equation of heat convection coefficient and proposed a more convenient modified equation:

$$h_{co} = \left\{ \left[1.51 \left(\frac{\Delta T}{l} \right)^{1/4} \right]^6 + (1.33 \Delta T^{1/3})^6 \right\}^{1/6} \quad (2)$$

$$h_{co} = 0.216 \left(\frac{\Delta T}{l} \right)^{1/5} \quad (3)$$

Eq (2) is used to calculate the heat convection coefficient on the vertical surface, Eq (3) is used to calculate the heat convection coefficient on the horizontal surface.

2.2. Mathematical model

In this paper, for the purpose of describing thermal storage performance and indoor temperature regulation effects of the internal envelope with nonlinear heat capacity, some assumptions were made as follows.

- Lightweight materials are used in the building exterior envelope, so that the influence of the exterior wall heat capacity on indoor thermal environment can be ignored.
- Ignoring the heat transfer process between each rooms.
- In order to display independently the impact rules of the idealized building internal wall thermal capacity on the indoor temperature, the thermal conductivity of the internal wall is large enough to satisfy the condition of Biot (Bi) < 0.1, then the inner and outer temperature of the internal wall would be the same, so the heat transfer process of internal wall can be analyzed with the lumped parameter method.
- The internal wall with PCM would maintain a homogeneous distribution.
- The idealized passive building does not install auxiliary heating equipment.

Based on above assumptions, simplified mathematical models for the analysis of the thermal performance of idealized passive building with PCM have been derived as follows:

The mathematical model of the indoor thermal environment of buildings is described by Eq (4):

$$V\rho_a c_{pa} \frac{\partial T_{in}}{\partial T} = h_{in} F_{in} (T_w - T_{in}) + U_w F_w (T_{out} - T_{in}) + U_{win} F_{win} (T_{out} - T_{in}) + NV\rho_a (T_{out} - T_{in})/3600 \quad (4)$$

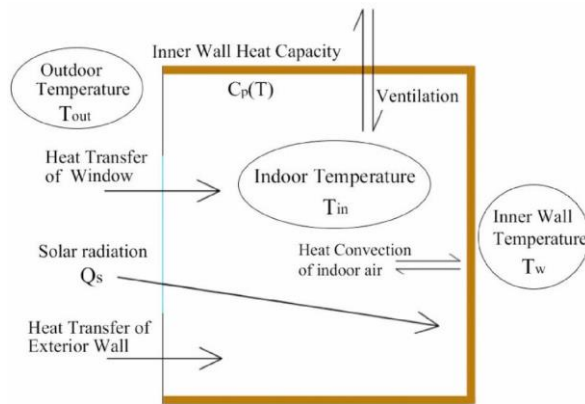


Fig. 2. The simplified model of the heat transfer process in nZEB.

Table 1

The physical properties of nZEB.

parameter	symbol	numerical
The length of the room(m)	L	4.5
The width of the room(m)	W	3.6
The height of the room(m)	H	2.7
The volume of the room(m^3)	V	43.74
The exterior wall area (m^2)	F_w	4.86
The internal wall area (m^2)	F_{in}	31.59
Interior convection heat transfer coefficient ($W/(m^2K)$)	h_{in}	8.7
Outdoor convection heat transfer coefficient ($W/(m^2K)$)	h_{out}	18.6
Overall heat transfer coefficient of exterior wall ($W/(m^2K)$)	U_w	0.2
Heat transfer coefficient of windowl ($W/(m^2K)$)	U_{win}	1.0
The internal wall volume(m^3)	V_w	1.0
Ventilation frequency(air change/h)	N	0.5

The mathematical model of the heat transfer process of the internal building envelope structure is described by Eq (5)

$$m_w c_{pw}(T_w) \frac{\partial T_w}{\partial t} = h_{in} F_{in} (T_{in} - T_w) + Q_s F_{win} \quad (5)$$

The initial condition is given by Eq (6) and Eq (7):

$$T_w = T_{init} \quad (6)$$

$$T_{in} = T_{init} \quad (7)$$

Where: V – is the volume of the room, m^3 .

ρ_a – is the density of the air, kg/m^3 ;

c_{pa} – is the heat capacity of the air,

$J/(kg \cdot K)$;

t – is the time, s ;

h_{in} – is the heat convection coefficient of indoor air, $W/(m^2K)$;

F_{in} – is the area of the inner wall, m^2 ;

U_{win} – is the overall heat transfer coefficient of the window, $W/(m^2K)$

N – is the number of air change, air change/h;

T_w – is the temperature of the wall surface, K ;

T_{in} – is the indoor temperature, K ;

T_{out} – is the outdoor temperature, K ;

F_{win} – is the area of the window, m^2 ;

m_w – is the quality of the wall, kg ;

c_{pw} – is the heat capacity of the wall, $J/(kg \cdot K)$;

T_{init} – is the set of initial temperature, K ;

Q_s – is the heat transfer rate of the window, W/m^2 ;

U_w – is the overall heat transfer coefficient of the wall surface, $W/(m^2K)$.

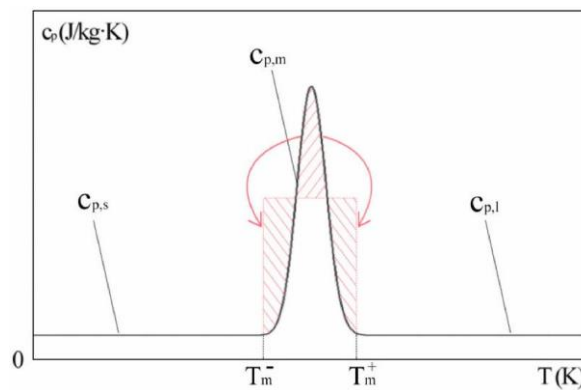


Fig. 3. The equivalent heat capacity of nonlinear heat capacity materials.

When the wall heat capacity ($c_{pw}(T_w)$) is constant, this model can be applied to idealized nZEB with CESM. The mathematical model is also suitable for situations where the thermal capacity of the building material would vary with temperature. The variation relationship between the specific heat $c_p(T)$ of PCM and temperature is shown in Fig. 3. In order to simplify the establishment method of heat capacity during the calculation process, the heat

capacity of PCM could be divided into a three-section expression method. The $c_p(T)$ is regarded as a fixed value during the phase change process which equals to the latent heat during the unit phase transition temperature range.

According to the requirements of 'technical standard for nearly zero energy buildings (GB/T 51350-2019)' [32], the thermal parameters of nZEB with PCM or CESM are shown in Table 2.

Besides the internal wall of the nZEB with PCM, the thermal parameters, structure parameters, climatic conditions and operating parameters of the building are the same with the nZEB with CESM. The latent heat of PCM was 100 MJ/m³. And the phase transition temperatures of PCM were 12 °C, 16 °C, 20 °C, 24 °C, 28 °C for the different simulation calculation conditions. The phase transition temperature range was 1 °C.

2.3. Evaluation parameters

The heat capacity of the internal envelope of the room mainly determines the indoor thermal energy storage capacity. It is closely related to the fluctuation of indoor temperature regulation. In order to evaluate the indoor temperature regulation effect by different heat capacity of internal envelope, the following indexes definitions are used:

- (1) The frequency distribution of indoor temperature. This parameter can show the stability of indoor temperature. The frequency distribution of indoor temperature is defined by Eq (8). First, the indoor temperature distribution conditions of the building during heating season were obtained by simulation. Then, counting the ratio of the occurrence time of indoor temperature at each of temperature regions and the entire heating time to get the frequency distribution of each temperature.

$$P(T_{in,i}) = \frac{\sum \tau(T_{in,i})}{24N} \quad (8)$$

Where: i - is the integer temperature region.

$\sum T_{in,i}$ - is the indoor temperature, K;

$\tau(T_{in,i})$ - is the accumulated time of indoor temperature occurrence, h;

$P(T_{in,i})$ - is the indoor temperature occurrence frequency during the heating season, %;

N - is the number of days of heating, d.

For example, the heating season in Beijing is 2904 h. In order to obtain the frequency distribution of indoor temperature at 16 °C, the hours of temperature at 15.5–16.5 °C were counted. Divide the hours of 15.5–16.5 °C by 2904 h to get the frequency of indoor temperature at 16 °C. The indoor temperature at the highest frequency is called as maximum frequency temperature.

- (2) The guarantee ratio for the setting temperature. The index counts the cumulative occurrence frequency of the indoor temperature which is larger than the setting indoor temperature during heating season. This index reflects the heating guarantee ratio of the nZEB with PCM when the indoor temperature is larger than the setting temperature. This index reflects the sum of indoor temperature frequency higher than the setting temperature, which is defined by Eq (9).

$$G(T_{set}) = \sum_{T_{in,i} \geq T_{set}} P(T_{in,i}) \quad (9)$$

- (3) The comfort guarantee ratio of nZEB. The building in the study was located in Beijing, it is necessary to research the range of indoor comfortable temperature in Beijing. Xu et al. [34] studied the comfortable indoor temperature range of buildings in Beijing by CPMV model and survey methods, the correlation between indoor temperature and people's satisfaction was obtained. Cao et al. [35] studied the appropriate indoor temperature in Beijing and found the differences in comfortable adaptability with people from different areas. By referring to these studies, the comfortable indoor temperature in winter in Beijing can be regarded as 16–24 °C. If the indoor temperature is within this temperature range, it can be regarded as the indoor comfort is

satisfactory. This index reflects the proportion of indoor comfort time in the whole heating season. The comfort guarantee ratio is defined by Eq (10).

$$P(T_c) = \frac{\sum \tau(T_c)}{24N} \quad (10)$$

Where: T_c - is the comfortable indoor temperature, K;

$\sum \tau(T_c)$ - is the accumulated time of indoor temperature in comfort range occurrence, h;

$P(T_c)$ - is the indoor temperature in comfort range distribution frequency during the heating season, %;

N - is the number of days of heating, d.

When the indoor temperature is higher than the upper limit of the comfortable temperature, it can be called as overheat. And when the indoor temperature is lower than the lower limit of the comfortable temperature, it can be called as underheat.

- (4) The latent heat utilization time ratio of PCM. This index reflects the ratio of the time of the PCM in phase transition state to the time of the whole heating season. Even if the PCM is used in the building components, the material cannot be guaranteed being in phase transition state for a long time during the heating season. The latent heat utilization time ratio of PCM can be defined by Eq (11). If the PCM selection is not appropriate, the time of phase transition state would be very short, so that PCM would only has little thermal storage performance and indoor temperature regulation effect. So the PCM used properly should have a large latent heat utilization time ratio.

$$P(u) = \frac{\sum \tau(u)}{24N} \quad (11)$$

Where: $P(u)$ - is the latent heat utilization time ratio of PCM, %;

$\sum \tau(u)$ - is the accumulated time of temperature of PCM in phase transition temperature range occurrence, h;

N - is the number of days of heating, d.

- (5) The phase transition temperature range of PCM. This index reflects the temperature difference between the initial temperature and the end temperature of PCM phase transition. The phase transition temperature range of PCM is defined by Eq (12).

$$\Delta T_m = T_m^+ - T_m^- \quad (12)$$

Where: T_m - is the phase transition temperature range, K;

T_m^+ -is the initial phase transition temperature,K;

T_m^- -is the end phase transition temperature,K;

Table 2

The thermal properties of nZEB.

parameters	numerical	parameters	numerical
The overall heat transfer coefficient of exterior wall(W/m ² K)	0.2	The overall heat transfer coefficient of window(W/m ² K)	1
Ventilation frequency(air change/h) Indoor	0.5	Shading coefficient of window	0.7
thermal disturbance(W/m ²)	4.5	The window wall ratio of exterior wall	0.6

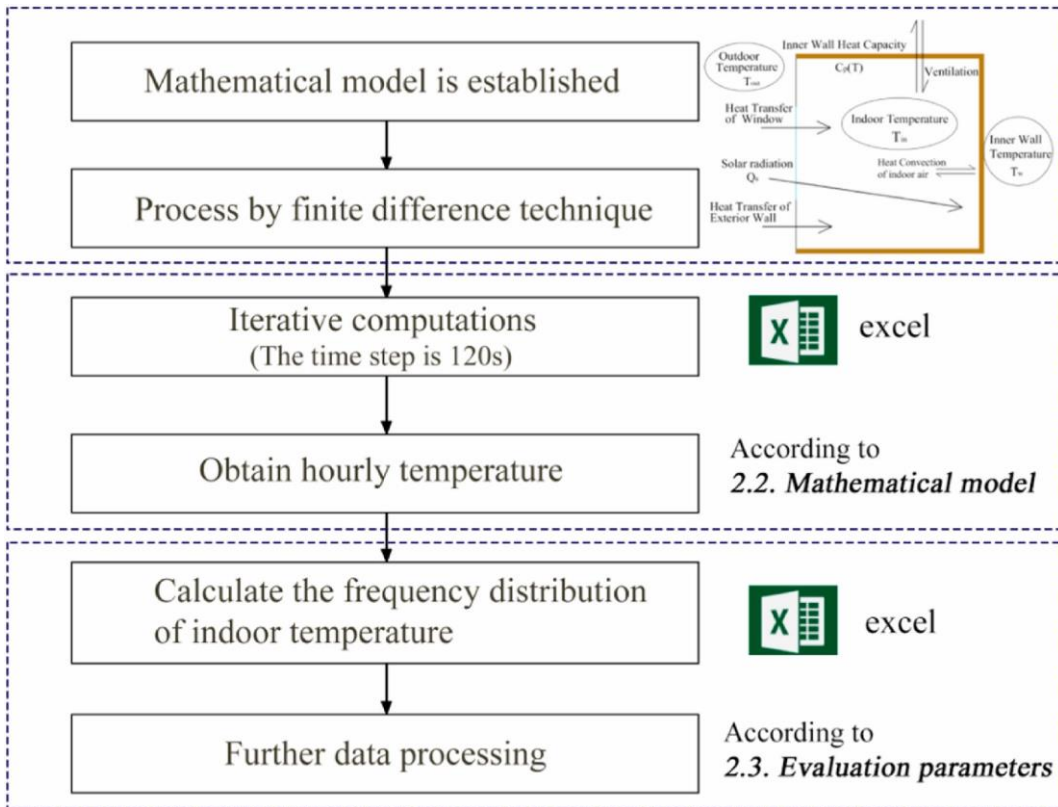


Fig. 4. The flow diagram of simulation steps.

For example, if the PCM with phase transition temperature at 24 °C and the phase transition temperature range is 1°C. Then its initial and end temperatures of phase transition are 23.5 °C and 24.5 °C can be found by Eq (12).

According to the mathematical model and thermal performance evaluation parameters established above, it could use the spreadsheet to simulate the temperature regulation characteristics of nZEB quickly. The specific calculation process is shown in Fig. 4.

To verify the reliability of the simplified model in this paper, reliability estimate has been done to compare with the results of the simulation by state-space method. The state-space method is a computational method to accurately simulate the dynamic heat transfer process of buildings, and its dynamic heat transfer model and algorithm have been verified by scholars [36–38]. Using the state-space method, a detailed mathematical model of the room with identical structural parameters is established and the method of nonlinear heat capacity was same as described in chapter 3.1. The phase transition temperature of PCM was 16 °C, guarantee ratio and frequency distribution of indoor temperature were calculated, and the simulated results was compared with the simplified model, as shown in Fig. 5. The difference of maximum frequency temperature between the two algorithms was only 1 °C, and the maximum distribution frequency were almost equal. The guarantee ratio calculated by the two algorithms are also very similar when the indoor temperature is below 30 °C. Therefore, the accuracy of this simplified model can be satisfactory when calculating the temperature regulation characteristics by nonlinear heat capacity building components.

3. Results and discussion

3.1. Thermal performance of nZEB with CESM

The frequency distribution of indoor temperature in the nZEB with CESM during the heating season is shown in Fig. 6. The frequency distribution of indoor temperature in the nZEB with CESM tends to be normally distributed. So the distribution frequency of highest and lowest indoor temperature appears little time. When the heat capacity of

the nZEB with CESM is changing in the region of $1 \sim 10\text{MJ}/(\text{m}^3\text{K})$, the maximum indoor temperature distribution frequency of the nZEB with CESM would not exceed 10%.

With the increase of the heat capacity within the building envelope structure, the maximum frequency temperature would be closer to the average indoor temperature. Compared with building with small heat capacity, building with large heat capacity has better indoor temperature stability and smaller indoor temperature variation region. For the purpose of improving the maximum frequency temperature, raising heat gain or reducing heat loss to improve the average indoor temperature is necessary. As shown in Fig. 6, the average indoor temperature of the nZEB with CESM is about $21\text{ }^\circ\text{C}$.

The guarantee ratio for the setting temperature of nZEB with CESM is shown in Fig. 7. With increasing building heat capacity, the indoor temperature distribution region becomes smaller. Increasing the building heat capacity can raise the minimum indoor temperature of the building. If setting temperature at $20\text{ }^\circ\text{C}$ is regarded as the reflection index of indoor temperature guarantee ratio of nZEB, the nZEB indoor temperature guarantee ratio of CESM with heat capacity of $10\text{MJ}/\text{m}^3\text{K}$ could exceed 60%, while the nZEB of CESM with heat capacity of $1\text{MJ}/\text{m}^3\text{K}$ is the lowest. Because of the insulation performance of nZEB is very excellent, the average indoor temperature of the nZEB with CESM is about $21\text{ }^\circ\text{C}$, so the indoor temperature can be exceeded this standard most of the time. So, if the average indoor temperature of the nZEB with CESM is higher than the reflection index, the guarantee ratio at setting temperature could be improved by increasing building heat capacity.

3.2. Thermal performance of nZEB with PCM

The frequency distribution of indoor temperature of the nZEB with PCM is shown in Fig. 8. The frequency distribution of indoor temperature of nZEB with PCM has two main features. The one is that the nZEB with PCM can significantly improve the maximum indoor temperature distribution frequency. For example, the maximum indoor temperature distribution frequency of nZEB with CESM is about 8%, while that of nZEB with PCM can reach 42%. Besides, the maximum frequency temperature of nZEB with PCM would be closer to the phase transition temperature, while the maximum frequency temperature of the nZEB with CESM would be closer to the average indoor temperature. The other feature is that the larger temperature difference between the phase transition temperature and the average indoor temperature, the smaller maximum indoor temperature distribution frequency would be. For example as shown in Fig. 8, the average indoor temperature of the nZEB with PCM is about $22\text{ }^\circ\text{C}$. When the phase transition temperature is $18\text{ }^\circ\text{C}$ – $26\text{ }^\circ\text{C}$, the maximum frequency temperature would be higher than that with other phase transition temperature.

Therefore, using PCM in nZEB can make the indoor temperature more centrally, it has a better effect on indoor temperature regulation than the CESM. The indoor temperature of nZEB can be controlled for a longer time by PCM with ideal temperature in theory. And the phase transition temperature of PCM should be determined according to average indoor temperature.

The guarantee ratio for the setting indoor temperature of the nZEB with PCM is shown in Fig. 9. It can be seen from the figure that the nZEB with PCM could significantly improve the guarantee ratio for the indoor temperature around the phase transition temperature. When the phase transition temperature is close to the average indoor temperature, the guarantee ratio for the indoor temperature around the phase transition temperature would become larger. For example, when the phase transition temperature of the PCM is $24\text{ }^\circ\text{C}$, the average indoor temperature is around $22\text{ }^\circ\text{C}$, the guarantee ratio for the indoor temperature above $20\text{ }^\circ\text{C}$ can reach 80.6%.

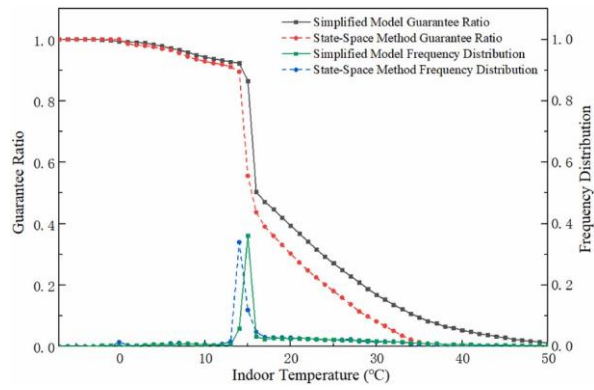


Fig. 5. Reliability estimate of simplified model by State-Space Method.

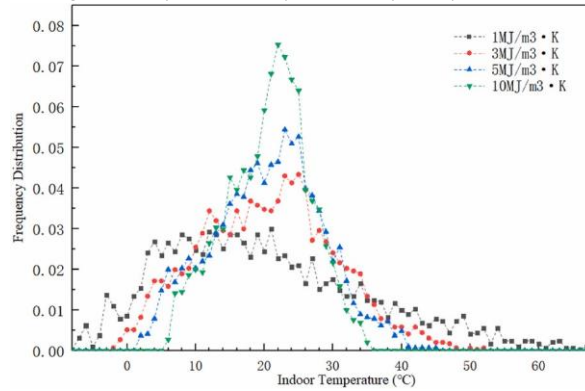


Fig. 6. The frequency distribution of indoor temperature of nZEB with CESM.

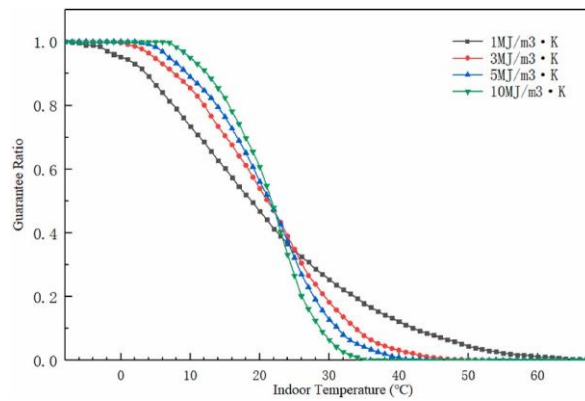


Fig. 7. The guarantee ratio for the setting of indoor temperature of the nZEB with CESM.

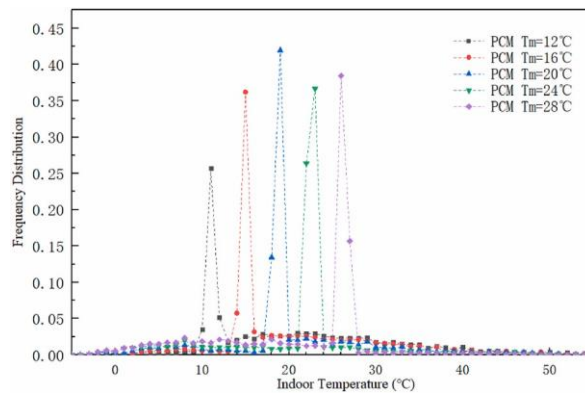


Fig. 8. The frequency distribution of indoor temperature of nZEB with PCM.

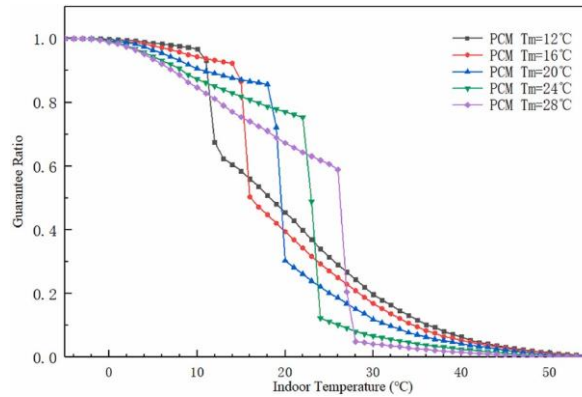


Fig. 9. The guarantee ratio for the setting of indoor temperature of nZEB with PCM.

While, even if the heat capacity of the CESM reaches $10\text{MJ}/\text{m}^3\text{K}$, the guarantee ratio for the indoor temperature above $20\text{ }^\circ\text{C}$ only can reach 60.7%, it is more lower than that of the PCM with phase transition temperature at $24\text{ }^\circ\text{C}$.

Therefore, nZEB with PCM can significantly improve the guarantee ratio for the setting indoor temperature by selecting an appropriate phase transition temperature. So the thermal storage performance and indoor temperature regulation effect according to the indoor temperature requirements can be achieved.

If the phase transition temperature selection is not close to the average indoor temperature, the thermal storage performance and indoor temperature regulation will be bad. For example, as for the nZEB with PCM, the guarantee ratio for indoor temperature above $20\text{ }^\circ\text{C}$ is 45.4% when the phase transition temperature is $12\text{ }^\circ\text{C}$. It is lower than the guarantee ratio for indoor temperature of the nZEB with CESM. So, inappropriate phase transition temperature would reduce the thermal storage capacity and indoor temperature regulation effect of the nZEB.

In order to intuitively show the difference of the nZEB with different heat capacity materials, the boxplot of the indoor temperature of nZEB is shown in Fig. 10. It can be seen from the figure that the closer phase transition temperature of PCM is to the average indoor temperature, the more concentrated the indoor temperature distribution is. When the phase transition temperature of the PCM is $24\text{ }^\circ\text{C}$, the indoor temperature distribution is most concentrated, and the indoor temperature can be easily controlled within the comfortable temperature range. The indoor temperature distribution of nZEB with CESM is significantly more dispersed than that of PCM. Although the heat capacity of CESM has reached $10\text{MJ}/\text{m}^3\text{K}$, the distribution of temperature in the statistical range of 25%–75% in the boxplot are still much more dispersed than using PCM. This is because the temperature of internal wall continues to rise during the solar radiation absorbed. At night, due to the decrease of outdoor temperature, indoor air temperature and internal wall temperature would continue to decline, so the indoor temperature has a strong fluctuation. The temperature of the inner wall with nonlinear heat capacity will be distributed close to the phase transition temperature, so the indoor temperature fluctuation would be very low.

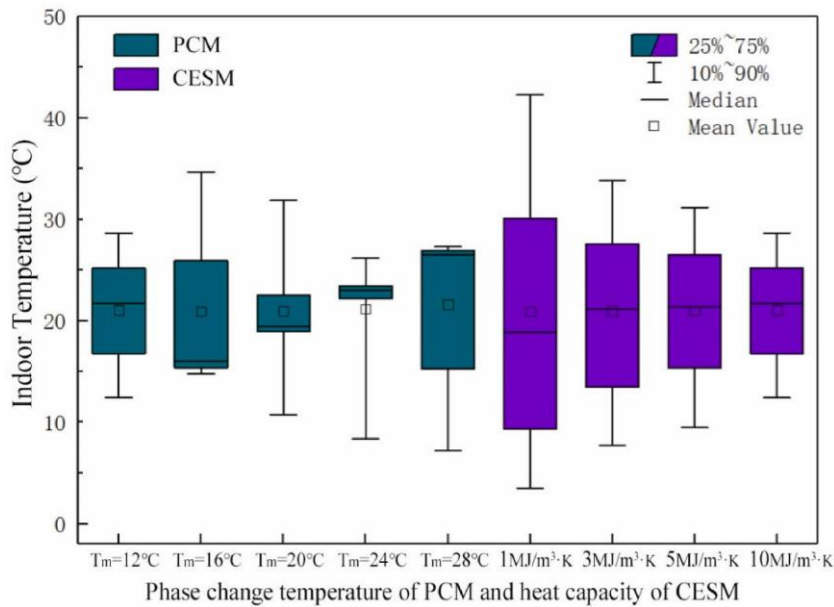


Fig. 10. The boxplot of the indoor temperature of nZEB with PCM and CESM.

The thermal storage performance and indoor temperature regulation effect of PCM could be reduced if the phase transition temperature is not appropriate. The main reason is that the latent heat utilization time ratio of the PCM has not enough, so it has not been in phase transition state for a long time. By counting the total time of PCM being in phase transition state during the whole heating seasons, the latent heat utilization time ratio of PCM would be obtained, as shown in Fig. 11.

For the nZEB with the average indoor temperature at 22 °C, the latent heat utilization time ratio of PCM can reach 52.9%–62.5% when the phase transition temperature between the region of 20–28 °C. As a result, the lower temperature difference between the phase transition temperature and the average indoor temperature, the higher latent heat utilization time ratio of the PCM has.

The results of guarantee ratio with different reflection temperature of the PCM and the best performing CESM are shown in Fig. 11. The latent heat utilization time ratio and guarantee ratio with different reflection temperature of PCM are studied together. It is found that PCM with phase transition temperature of 24 °C can guarantee the high latent heat utilization time ratio, and the guarantee ratio of 18–24 °C is relatively high. PCM with phase transition temperature of 20 °C and 28 °C has more than 50% latent heat utilization time ratio, so it can also get high guarantee ratio at some specific indoor temperature requirements. Therefore, it can be considered that there is an interaction between the latent heat utilization time ratio and the temperature guarantee ratio. Compared with nZEB using CESM and PCM with different phase transition temperature, the temperature guarantee ratio of CESM did not exceed PCM when the different reflection temperature of guarantee ratio were selected, so the PCM has advantage of temperature regulation effect in nZEB.

Different phase transition temperature range of PCM in nZEB was selected to study the influence of the width of phase transition temperature range of PCM on the indoor temperature regulation in the nZEB. The phase transition temperature of PCM was 24 °C has the highest performance in above studies. The equivalent specific heat capacity of PCM with phase transition temperature at 24 °C in different phase transition temperature ranges was shown in Fig. 12. The total heat capacity of different phase transition temperature ranges is equal, so the areas under different curves would be equal. Therefore, narrower phase transition temperature range of the PCM has higher peak value of specific heat capacity curve.

The boxplot of the statistical results of indoor temperature of different phase transition temperature range and the CESM with heat capacity as 10MJ/m³K was compared, it is shown in Fig. 13. The PCM with narrower phase transition temperature range has higher indoor temperature concentration in nZEB. When the phase transition

temperature range was 0.5 °C, 25%–75% of the indoor temperature was concentrated at 23–24 °C. Which was significantly more concentration than the PCM with phase transition temperature range was 4 °C.

PCM with different phase transition temperature ranges in Fig. 13 were all satisfy the indoor temperature regulation requirements of nZEB, and all of the average phase transition temperature in figure were 24 °C. It can be found that for the nZEB with PCM, the average phase transition temperature of PCM has a higher impact than the width of phase transition temperature ranges for the indoor temperature regulation. The PCM in different phase transition temperature ranges was compared with CESM. Even the PCM with a wide phase transition temperature range, it has better indoor temperature regulation effect than that of CESM when the average phase transition temperature is suitable.

3.3. The comfort guarantee ratio of nZEB

The comfortable indoor temperature range in winter is 16–24 °C, and if the indoor temperature is within this temperature range, it can be regarded as the indoor comfort is satisfactory, which defined by Eq (10). The comfort guarantee ratio of nZEB with CESM and PCM was compared. It can be seen from Fig. 14 that PCM with phase transition temperature at 24 °C and 20 °C can reach more than 60% of the comfort guarantee ratio, while CESM with 10MJ/m³K can only reach 44.9% of that. The indoor temperature of nZEB with PCM using phase transition temperature at 20 °C and 24 °C have higher indoor comfort ratio, because their phase transition temperature is very close to the average indoor temperature. The nZEB using PCM has a more concentrated indoor temperature within a small range, while the nZEB using CESM has a more uniform indoor temperature distribution. Therefore, PCM is more accurate for indoor temperature regulation, and plays a positive role in improving indoor comfort guarantee ratio.

It can be seen from Fig. 15 that the reasons of the nZEB using PCM with appropriate phase transition temperature has higher indoor comfort guarantee ratio for another perspective. In Fig. 15 the blue part on the left is the ratio of the underheat time in heating season, the red part on the right is the overheat time in the heating season, and the green part in the middle is the indoor comfort guarantee ratio of nZEB. Due to excellent thermal insulation of nZEB and full use of solar radiation, the indoor temperature of nZEB with CESM is often higher than the comfortable indoor temperature limit, and it indirectly results insufficient heating in some other time. Therefore, too much of underheat time or overheat time will lead to reduced indoor comfort guarantee ratio.

The proportion of indoor temperature underheat time of nZEB with PCM, which phase transition temperature at 20 °C and 24 °C were only 13% and 19%, and the proportion of overheat time were only 22% and 12%, respectively. The proportion of overheat time of indoor temperature of nZEB with CESM is between 30% and 40%, which is much higher than that of PCM with phase transition temperature close to the indoor average temperature. And the proportion of indoor temperature underheat time also shows a similar pattern. This is because the heat capacity of PCM during phase transition is very large, so it can charge or discharge heat at almost constant temperature for a longer time. If the phase transition temperature of PCM within the comfort temperature range, it can control the indoor temperature within the comfort temperature range by its large heat capacity. So reducing the time of underheat and overheat of indoor temperature, and the comfort guarantee ratio of indoor temperature will be high. If the phase transition temperature of PCM is inappropriate, it will cause the low heat capacity within the comfort temperature range and the high heat capacity outside the comfort temperature range, so the indoor comfort guarantee ratio of using PCM with inappropriate phase transition temperature will be lower than that of CESM. So the PCM with phase transition temperature close to the indoor average temperature can control the indoor temperature more concentrated and has higher comfort guarantee ratio.

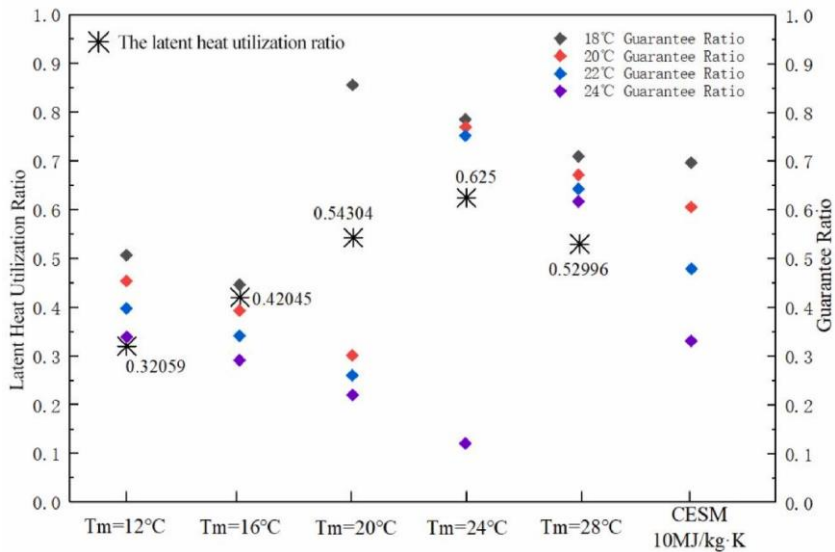


Fig. 11. The latent heat utilization time ratio of nZEB with PCM.

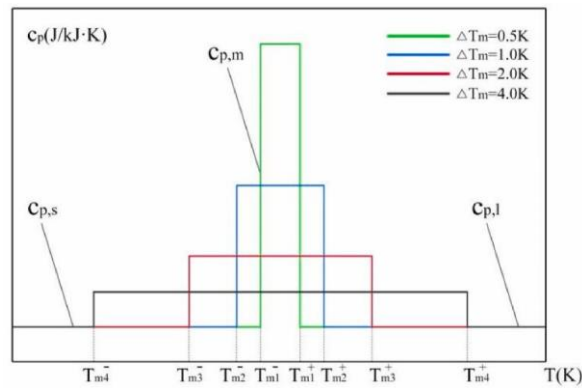


Fig. 12. Different phase transition temperature range of PCM.

4. Conclusions

Nearly zero energy building has high solar radiation utilization and well thermal insulation performance, it can use heat storage performance of the inner envelope to passively regulate the indoor temperature. As a nonlinear heat capacity material, PCM can be used in building interior walls to regulate indoor temperature. In order to analyze the indoor temperature regulation characteristics for the nZEB with PCM, traditional simulation methods are often very complex. To simplify the simulation method, a simplified mathematical model was established, which can simulate the temperature regulation characteristics affected by the nonlinear heat capacity building components quickly. The evaluation indexes reflecting the thermal performance of the nZEB were put forward, and the effect of the nonlinear heat capacity on the evaluation indexes were shown as follows.

- (1) The PCM presented significant effect on the indoor temperature regulation of nZEB. The indoor temperature guarantee ratio with PCM building components can be regulated by changing the phase transition temperature. The maximum indoor temperature distribution frequency and the indoor temperature guarantee ratio can achieve highest value when the phase transition temperature is close to the average indoor temperature in the heating season. When the phase transition temperature at 20 °C, the indoor temperature guarantee ratio of 18 °C and the maximum indoor temperature distribution frequency in the nZEB could reach 85.6% and 42%, respectively.

- (2) The maximum indoor temperature distribution frequency of the nZEB with PCM building components was significantly larger than that with the CESM. PCM could make the maximum indoor temperature distribution frequency in nZEB 4.2 times higher than that of CESM.

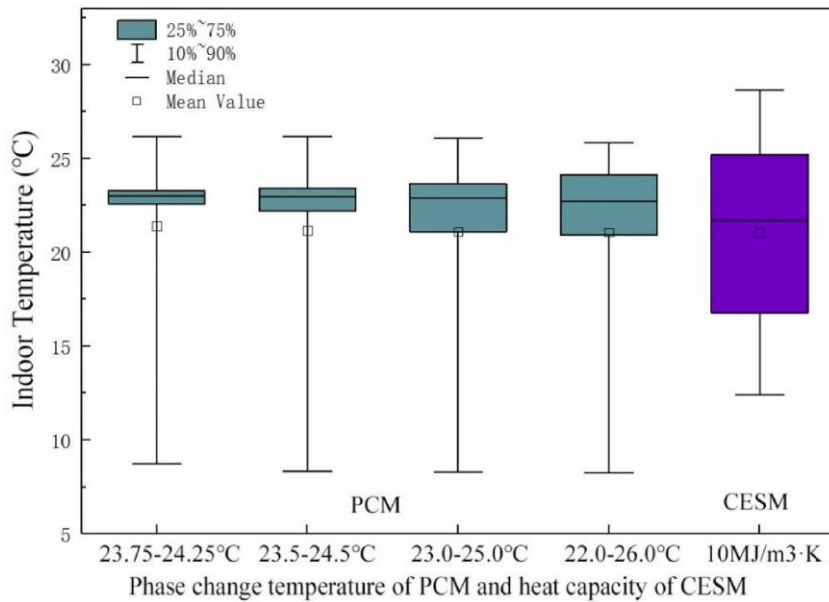


Fig. 13. The boxplot of the indoor temperature of nZEB with different phase transition range of PCM.

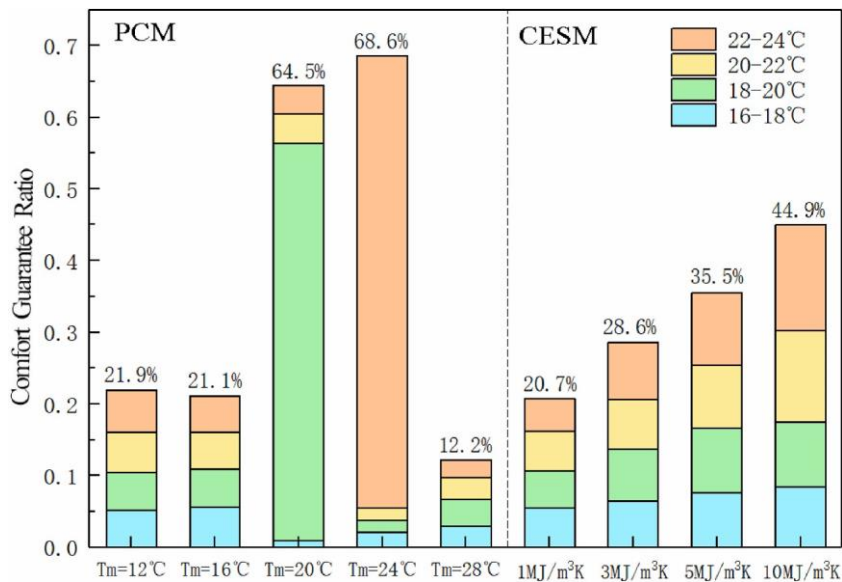


Fig. 14. The Comfort guarantee ratio of the indoor temperature of nZEB with PCM and CESM.

- (3) The latent heat utilization time ratio of PCM were affected by the phase transition temperature. In order to make the latent heat utilization time longer, the phase transition temperature should be close to the indoor average temperature. The latent heat utilization time ratio of PCM at appropriate temperature can reach 0.625.
- (4) The phase transition temperature of PCM close to the indoor average temperature could regulate the indoor temperature within the comfortable temperature range for a long time. The overheat and underheat ratio of nZEB with PCM were both less than 20%, and the comfort guarantee ratio could reach most by 69%.

In this study, the indoor temperature regulation characteristics for the nZEB with nonlinear heat capacity building components was analyzed by a simple model. However, this mathematical model has some limitations. The major limitations of the present study is the simple model is only suitable for ideal lightweight buildings, but it didn't work when the building envelope has high heat capacity. In addition, the temperature of the heat storage material is assumed to be uniform. However, if the solar radiation irradiation is not uniform, the temperature of the thermal storage material is not uniform, the model will not be applicable.

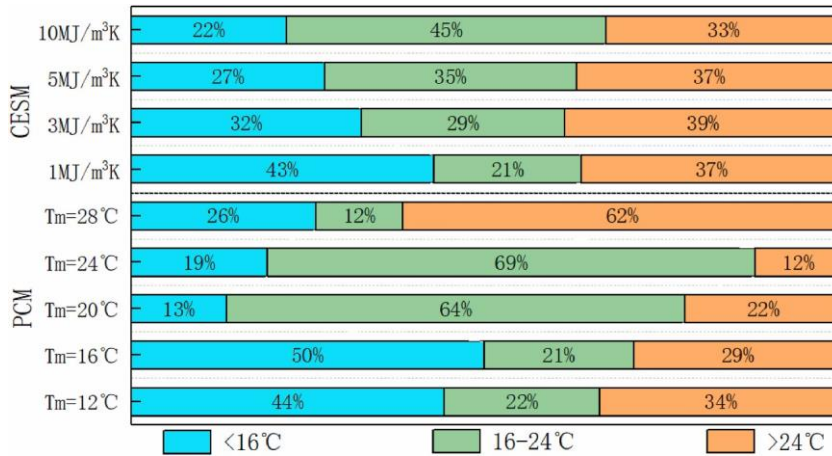


Fig. 15. The distribution of the indoor temperature of nZEB with PCM and CESM.

In future work, the influence of building envelope heat capacity on indoor temperature regulation effect, temperature distribution of heat storage materials, and the indoor temperature regulation characteristics under summer conditions should be considered.

Author statement

Qunli Zhang: Conceptualization, Methodology, Project administration, Yimo Liu: Writing - Original Draft, Writing - Review & Editing, Formal analysis, Qiuyue Zhang: Investigation, Validation, Gang Wang: Investigation, Xiaoshu Lü: Writing - Review & Editing.

Declaration of competing interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. All authors contributed equally in the preparation of this manuscript.

Data availability

Data will be made available on request.

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