Thermal stress performance of glazed units contained phase change material

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Abstract
The low heat transfer and high energy storage performance of phase change material (PCM) will improve the thermal performance of the PCM-glazed units. However, decreasing the heat transfer results in uneven thermal load on the surface of the PCM-glazed units, which is an important cause of thermal stress in such units, because the glass in glazed units is a fragile material, and then large thermal stress can result in cracks and possible fallout of the glazed units. To study the thermal stress distribution of PCM-glazed units, a method combined numerical simulation and experimental analysis was conducted. First, the heat transfer performance and thermal stress distribution of PCM-glazed units with PCM thicknesses between 3 and 11 mm were experimentally investigated. Results showed that the thermal performance of a glazed unit was improved by adding PCM, and the variation of thermal strain on its surface with a PCM-layer thickness of 7 mm was the smallest in five test facilities. Then, the thermal stress was numerically investigated regarding the PCM height and the aspect ratio of the PCM-glazed unit. The higher the PCM height, the greater the maximum strain. An aspect ratio of PCM-glazed units of 1.5 was recommended.

Keywords
Glazed unit, Phase change material, thermal stress, thermal performance, Phase change material layer thickness

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Introduction

Reducing the world’s total energy demand and energy consumption has become a strategic global goal (Abu-Jdayil et al., 2019; Wang et al., 2017). Buildings play a key factor in energy saving as their energy usage accounts for over 40% of the world’s primary energy use (Misiopiecki et al., 2018). Glazed units in the form of windows and roofs are important in buildings as they provide visibility, air ventilation, passive solar gain, and daytime lighting (Arıcı et al., 2015; Thalfeldt et al., 2016; Xamán et al., 2020). Diversified dimensions of glazed units are required as a result of an architectural movement to improve the building aesthetics (Pérez-Grande et al., 2005). However, the thermal performance of glazed units is much poorer than any other envelope structure of buildings (Flores Larsen et al., 2015; Liu et al., 2017; Loem et al., 2019), and thus glazed units have become a critical element in the energy consumption of buildings (Li et al., 2020a, 2020b). Therefore, more attention has been paid to the new energy-saving glass increasingly (Arıcı et al., 2015; Li et al., 2018a, 2018b, 2018c). Double-glazed units with phase change material (PCM) are one of the new types of energy-saving glass.

In recent years, the thermal and optical performance of PCM-glazed units has been extensively studied numerically and experimentally. For example, Liu et al. (2018) found that the influence of air convection on the thermal and optical performance of a multi-layer glazed roof was weak for different PCM melting temperature and thickness, except for its effect on the interior temperature. Park et al. (2019) employed Energy Plus to optimize the application of a glass curtain wall building integrating PCM, and evaluated building thermal performance compared with conventional buildings. Goia et al. (2015) measured reflectance, transmittance, and absorptance spectra of double-glazed units characterized at different incident-beam angles for different PCM-layer thicknesses in the gap of glazing systems, providing a dataset of luminous and solar properties of glazing units with PCMs. Li et al. (2016a, 2016b, 2018a, 2018b, 2018c) showed that the temperature time lag of a PCM-filled double-glazed unit increases and the temperature decrement factor decreases with increasing density, specific heat capacity, thermal conductivity, latent heat, and melting temperature of PCM. Salih et al. (2019) investigated the thermal performance of a double-pass solar air heater using multiple rectangular capsules filled with a paraffin-wax-based PCM, and showed that the increased airflow rate delays the melting period and decreases the melting temperature of the paraffin during the melting period. Gowreesunker et al. (2013) experimentally and numerically revealed the optical and thermal aspects of a PCM-glazed unit, and the results showed that the addition of PCM improves the thermal mass of the unit during phase change. Liu et al. (2017) investigated the influence of the thickness and melting temperature of PCM on the thermal performance of double glazed units, and recommended PCM-layer thicknesses between 12 and 30 mm for building applications in northeast China. Arıcı et al. (2015) investigated the thermal performance of glass windows composed of glass, silica aerogel, and PCM, and results showed that integrating silica-aerogel insulation into a PCM-glass window system is an effective technology in cold regions.

From the above literatures, with the help of the energy storage performance of PCM (Cetina-Quiñones et al., 2021; Triano-Juárez et al., 2020), PCM-glazed units possess a good energy storage performance. The energy savings of PCM-glazed units are mainly due to the low thermal conductivity and good energy storage performance of PCM (Lachheb et al., 2014; Moraga et al., 2014). Decreasing the heat transfer of PCM-glazed units (Li et al.,
creates uneven thermal load, which produces a temperature difference in PCM-glazed units (Wang et al., 2018), however a large temperature difference increases the thermal stress in such units. The glass in PCM-glazed units is fragile, which results that the PCM-glazed units become one of the most fragile and vulnerable components of buildings under load (Bedon et al., 2018), e.g., impact load (Olmos Navarrete et al., 2017) or thermal load (Wang et al. 2012). There are many studies on the thermal stresses of architectural glass. For example, Shields et al. (2001, 2005) reported the temperature-induced stress fields in single glass panes that revealed crack bifurcation patterns based on numerous experiments. Joshi and Pagni (1994) estimated thermal stresses over single glass panes with thermal load. Fan et al. (2016) revealed that the glass thickness has a great influence on the quenching period, temperature gradient, and stress field distribution. Wang et al. (2017) demonstrated the critical breakage conditions for double glazing in fire. Klassen et al. (2010) investigated double- and triple-pane glazing specimens with a laminate interlayer to measure the radiant transmission of energy and window-breakage characteristics of seven different multi-plane glazing samples. Li and Cheng (2001) established the fracture model of double-layer glass, and studied the heat transfer process of the inner surface of double-layer glass by experiment and numerical simulation, and predicted the breaking time of a glass window initially.

The above stated literatures are focused on the thermal stress of conventional single- and double-layer glasses. To the best of our knowledge, few literatures exist concerning the thermal stress analysis of PCM-glazed units. It is thus necessary to further understand the relationship between thermal performance and thermal stress of PCM-glazed units, especially such units with different dimensional parameters.

In present work, the effect of dimensional parameters on the thermal performance and thermal stress of PCM-glazed units, including PCM thickness, PCM height, and the aspect ratios of PCM-glazed units was explored. Combined numerical simulation and experimental analysis was conducted to reveal the relationship between the thermal performance and thermal stress distribution of PCM-glazed units under the above-mentioned parameters. The derived results can provide reference for the design PCM-glazed units for practical application in buildings.

**Methodology**

**Experimental setup**

The measurements were conducted at Northeast Petroleum University in Daqing City in northeast China, which is a severe cold zone with a big temperature difference between day and night (Meng et al., 2019). Five small-scale test facilities are shown in Figure 1. The test facilities have south-facing rooms with inner dimensions of 600 mm \( \times \) 600 mm \( \times \) 500 mm (Height \( \times \) Width \( \times \) Depth); the PCM-filled glazed units have dimensions of 400 mm \( \times \) 500 mm (Height \( \times \) Width). The thickness of glass layers in all the facilities is 5 mm. Since Liu et al. (2017) suggested that the PCM-layer thickness in the glazed units should be less than 16 mm in northern China, the studied PCM-layer thicknesses are 3, 5, 7, 9, and 11 mm in the present work. All the glazed systems were filled with PCM (paraffin, RT18), the thermophysical properties of which are shown in Table 1. The non-glass surfaces are coated with 50-mm-thick mineral wool as an insulating layer, as shown in Figure 1(c).
The strain of the PCM-glazed units was measured using resistance strain gauges (Type BF350-6AA) and static strain instrument (Model DH3818), which were manufactured by Donghua Testing Co., Ltd., China. The range of average resistance error of the resistance strain gauges is 0.1%, and the resistance error of static strain instrument is 1.5%.

The accuracy of the resistance strain gauges were shown in Table 2. The temperatures of the PCM-glazed units were measured with a multi-point test temperature detector (JTRG-II) and T-type thermocouples, manufactured by Beijing Century Jiantong Technology Development Co., Ltd., China, which were installed 5 mm from the strain gauges. The parameters of these instruments are shown in Table 3, and the arrangement and position of the measuring points are shown in Figure 2(b). To improve measurement reliability and accuracy, all devices were calibrated before each experiment.

The available experimental data shows that thermal breakage of window glass generally occurs at exposed edges (Wang et al., 2014). Considering that the edges of the glazed units were fixed, the resistance strain gauges and thermocouples were located at three symmetrical positions on the inner and outer surfaces of each glazed unit, as shown in Figure 2. Each

Table 1. Thermophysical properties of paraffin and glass.

| Material | Melting temperature (°C) | Density (kg/m³) | Thermal conductivity (W/(m·K)) | Specific heat capacity (J/(kg·K)) | Latent heat (J/kg) |
|----------|--------------------------|-----------------|-------------------------------|----------------------------------|-------------------|
| PCM      | Solid 18                 | 885             | 0.2                           | 2320                             | 185000            |
|          | Liquid 880               | 880             | 0.21                          | 2240                             |                   |
| Glass    |                          | 2500            | 1.3                           | 840                              |                   |

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measurement was repeated twice to enhance the reliability of the results. A set of experimental data was recorded by the experimental setup from 6:00 p.m. on 8 September 2019 to 6:00 p.m. on 9 September 2019, and another set of experimental data was acquired from 6:00 p.m. on 19 September 2019 to 6:00 p.m. on 20 September 2019.

**Mathematical model**

For the analysis of the heat transfer and thermal stress distribution, the following assumptions were made.

1. Compressive strength produced by PCM on glass is ignored.
2. The thermo-physical properties of PCM (thermal conductivity and specific heat capacity) are independent with temperature in the solid-liquid phase.

| Table 2. The parameters of BF350-6AA and DH3818. |
|--------------------------------------------------|
| **Resistance strain gauges (BF350-6AA)** | **Static strain tests of the system (DH3818)** |
| **Measurements** | **Accuracy** | **Measurements** | **Accuracy** |
| Sensitivity dispersion | ≤±1% | Resolution | 1 με |
| Sensitivity coefficient | 2–2.20 | Sensitivity coefficient | 2 |
| Temperature range | −30°C~80°C | System uncertainty | ≤0.5%±3 με |
| Average resistance error | ≤±0.1% | Resistance error of strain gauge | 1.5% |

| Table 3. The parameters of multi-point test temperature detector JTRG-II and T-type thermocouple. |
|--------------------------------------------------|
| **Measurements** | **Measuring range** | **Accuracy** | **Resolution** |
| Temperature (T-type Thermocouple) | −50°C~150°C | ±0.5°C | 0.1°C |
| Environment temperature (PT100 thermal resistance) | −40°C~50°C | ±0.1°C | 0.1°C |
| Heat flux | 0~1000 W/m² | ≤±5% | 0.1 W/m² |

**Figure 2.** Arrangement of temperature and strain measurement points (a: Arrangement of thermocouple and resistance strain gauges, b: Details of the location of the three measuring points).
(3) Thermal stress in the direction of glass thickness is ignored.
(4) Thermal-elastic deformation of glass is isotropic.
(5) On the glass pane, apart from thermal loading, no other mechanical loading exists (Zhang et al., 2020).

Since the thermal stress is produced by the temperature gradient in PCM-glazed units, the surface temperature of the PCM-glazed units should be calculated firstly, and then the thermal stress should be calculated based on the temperature result. Because the thermal stress on the surface of PCM-glazed units comes mainly from ambient temperature and solar radiation, the mathematical description of the problem is formulated below, which consists of governing equations of the optical, heat-transfer, and the thermal stresses.

**Governing equations of heat transfer.** For three-layer glazed unit containing PCM, the heat transfer includes different regions, i.e., the outer glazing and the PCM filled between glass layers.

The energy equation for glass layers is

$$\frac{\partial T}{\partial \tau} = \frac{k}{\rho c} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + S^T \quad (1)$$

where $T$ is the temperature (K); $\rho$ represents the density (kg/m$^3$), $k$ is thermal conductivity (W/(m$^2$K)), $c$ represents specific heat (J/(kg$^\circ$K)). $S^T$ is the radiation source (W/m$^3$) and $\tau$ is the time (s).

In the PCM layer, the heat transfer occurs by conduction and radiation. The unsteady energy equation for PCM regions is

$$\rho_p \frac{\partial H}{\partial \tau} = k_p \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + S^T \quad (2)$$

The specific enthalpy of the PCM is

$$H = \int_{T_{ref}}^{T} c_p dT + \beta L \quad (3)$$

$$\beta = \begin{cases} 
0 & T_s \leq T \\
\frac{T - T_s}{T_1 - T_s} & T_s \leq T \leq T_1 \\
1 & T \geq T_1
\end{cases} \quad (4)$$

where $\rho_p$ represents the density (kg/m$^3$) of the PCM. $k_p$ and $c_p$ represents thermal conductivity (W/(m$^2$K)) and specific heat (J/(kg$^\circ$K)) of the PCM. $T_{ref}$, $T_s$, and $T_1$ represent reference temperature, initial melting temperature and liquidus temperature (K) of the PCM, respectively. $\beta$ is the liquid fraction of PCM undergoing phase change. $L$ is the latent heat of the PCM (kJ/kg).
For the control volume, the source term $S_T$ in the conduction heat transfer equation is calculated by:

$$S_T = \int_{\Omega_i=4\pi} I(s,\vec{s}_i) \Omega d\Omega_i$$  \hspace{1cm} (5)$$

The radiative transfer equation for glass and PCM is given by (Modest, 1993) (Li et al., 2013, 2020a, 2020b):

$$\frac{dI(s,\vec{s})}{ds} = -(\alpha + \sigma)I(s,\vec{s}) + \frac{\sigma}{4\pi} \int_{4\pi} I(s,\vec{s'}) d\sigma + \alpha I_b(s,\vec{s})$$  \hspace{1cm} (6)$$

where $I(s,\vec{s})$ is the solar radiation intensity (W/m$^2$) in spatial position and direction. $\sigma$ and $\alpha$ are thickness (mm) and the medium absorption coefficient (1/m).

**Governing equations of thermal stress.** The thermal stress in PCM-glazed units is caused by the temperature difference. At present, there are many numerical methods that can be used to calculate the thermal stress. The finite-element method (FEM) is widely used to quantify the thermal stress in solid material. Therefore, it was used to analyze the thermal stress in the PCM-glazed units (Chow and Gao, 2008). For this work, the three-dimensional FEM was thus used. The basic equations of the FEM is

$$\left( \sum_{e=1}^{E} [K^{(e)}] \right) \vec{Q} = \vec{P}_c + \sum_{e=1}^{E} (\vec{P}_i^{(e)} + \vec{P}_s^{(e)} + \vec{P}_b^{(e)}) = \vec{P}$$  \hspace{1cm} (7)$$

where $[K^{(e)}]$ is the stiffness Matrix of element; $\vec{P}_i^{(e)}$ is the element load vector caused by the initial stress; $\vec{P}_s^{(e)}$ is the element load vector caused by surface stress; $\vec{P}_b^{(e)}$ is the unit load vector caused by the change in shape; $[D]$ and $[B]$ represent the elastic matrix and Strain-displacement Matrix, respectively.

The stiffness Matrix of element $[K^{(e)}]$, the element load vector $\vec{P}_i^{(e)}$, $\vec{P}_s^{(e)}$, $\vec{P}_b^{(e)}$ and $dV$ are

$$[K^{(e)}] = \iiint_{V^{(e)}} [B]^T [D] [B] dV$$  \hspace{1cm} (8)$$

$$\vec{P}_i^{(e)} = \iiint_{V^{(e)}} [B]^T [D] \vec{\epsilon}_0 dV$$  \hspace{1cm} (9)$$

$$\vec{P}_s^{(e)} = \int_{S^{(e)}} [N]^T \vec{\phi} dS_1$$  \hspace{1cm} (10)$$

$$\vec{P}_b^{(e)} = \iiint_{V^{(e)}} [N] \vec{\phi} dV$$  \hspace{1cm} (11)$$
\[ dV = dx\,dy\,dz = \det[J]\,dr\,ds\,dt \] (12)

For the three-dimensional thermal stress, the basic equation is

\[
\begin{align*}
\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + X &= \rho \frac{\partial^2 u}{\partial t^2} \\
\frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{zy}}{\partial z} + Y &= \rho \frac{\partial^2 v}{\partial t^2} \\
\frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + Z &= \rho \frac{\partial^2 w}{\partial t^2}
\end{align*}
\] (13)

where \( \sigma_x \) and \( \sigma_y \) are normal stresses in the \( x \)- and \( y \)-direction, respectively; \( \tau_{yx} \) and \( \tau_{xy} \) are the respective shear stresses; \( X, Y, \) and \( Z \) are the body forces in the \( x \)-, \( y \)-, and \( z \)-direction, respectively; \( u, v, \) and \( w \) are the corresponding displacements in the \( x \)-, \( y \)-, and \( z \)-direction; and \( t \) is the time. For the thermal stress calculation, the first step is to calculate the displacement by the displacement method, the second is to calculate the thermal strain, and the third is to calculate the thermal stress. If the temperature of the material in its initial state is known, then the corresponding strain can be calculated more easily. Similar to temperature variation, the displacement equation is obtained as follows using the Galerkin method:

\[
\int_D W_i \left[ \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + X - \rho \frac{\partial^2 u}{\partial t^2} \right] dx\,dy\,dz = 0 (l = 1, 2, \ldots, n) \] (14)

\[
\int_D W_i \left[ \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{zy}}{\partial z} + Y - \rho \frac{\partial^2 v}{\partial t^2} \right] dx\,dy\,dz = 0 (l = 1, 2, \ldots, n) \] (15)

\[
\int_D W_i \left[ \frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + Z - \rho \frac{\partial^2 w}{\partial t^2} \right] dx\,dy\,dz = 0 (l = 1, 2, \ldots, n) \] (16)

\[ \varepsilon_0 = [\alpha_1 \Delta T, \alpha_1 \Delta T, \alpha_1 \Delta T, 0, 0, 0]^T \] (17)

The stress-strain relationship becomes

\[ \sigma_1 = E(\varepsilon - \varepsilon_0) \] (18)

where \( \sigma_1 \) is the stress, and \( \varepsilon \) is the strain. \( E \) is the elastic modulus of glass, which is a constant. The strain was measured experimentally and was therefore used to explain the temperature stress on the surface of PCM-glazed units in this work.

For an isotropic material such as glass, an increase in temperature, \( \Delta T \), will cause the strains to be the same in different directions; the strains depend on the coefficient of thermal expansion of the material, \( \alpha_1 \), which represents a change in the length of a material as a
result of a rise in unit temperature caused. \( x_1 \) is assumed to be a constant, independent of temperature.

**Model validation**

The software ANSYS is used to analyze the thermal stress of the PCM-glazed units in this work. Coupled Field is used for simulations, and Brick 20 node 226 is used for calculations. The finite element program was verified by comparing the calculated results with the experimental results. The numerical conditions are set to be the same as those of the experiments, and the details are described as follows.

A triangle mesh was taken in the finite element calculation, and the size of the PCM-glazed unit was 400 mm \( \times \) 500 mm \( \times \) 17 mm (Height \( \times \) Width \( \times \) Thickness). The detailed conditions of the experiments described above were introduced to the numerical model. The material properties used in the simulation are presented in Table 4. The glazed unit filled with a PCM layer of thickness 7 mm was selected for the simulation. The primary thermal loading of experimental temperatures in the test facility at 12:00 a.m. on 9 September 2019, i.e., 20.5°C (outside ambient temperature) and 37.2°C (indoor ambient temperature), was selected. The comparison of simulated and measured strains on the surfaces of a PCM-glazed unit is shown in Figure 3. It is seen from Figure 3 that the curves of the simulated results and experimental data are almost the same in most regions. However, most of the simulated values are less than the experimental value, the reason is the linear expansion coefficient of glass is an important factor that affects the strain of glass. The linear expansion coefficient of glass varies with the temperature, while, the linear expansion coefficient of glass is set to a constant value and is small in the numerical simulation. The average relative value of the simulation result is 12.5%.

**Results and discussion**

**Experimental results**

The thermal performance of PCM-glazed units was investigated firstly, which was also the basis for the study of thermal stress. As mentioned above, five PCM-glazed units with different PCM thicknesses were measured twice in September 2019. The measured data of two experiments were similar, and a set of measuring data was selected for analysis. The experimental results are shown in Figure 4.

Figure 4 shows the measuring data of the internal temperature of the test facility with different PCM-layer thicknesses on 8 and 9 September 2019. The variation trend of the inner surface temperature of the glazed units with different PCM-layer thicknesses was found to

| Properties                                      | Symbol | Values       |
|-------------------------------------------------|--------|--------------|
| Young's modulus (Pa) (Chow and Gao, 2008)        | E      | \( 7.0 \times 10^{10} \) |
| Poisson’s ratio (Fabien et al., 2015)            | \( \nu \) | \( 2.2 \times 10^{-1} \) |
| Density (kg/m\(^3\)) (Fabien et al., 2015)      | \( \rho \) | \( 2.5 \times 10^{3} \) |
| Thermal expansion coefficient (\( ^\circ \)C) (Chow and Gao, 2008) | \( \alpha_1 \) | \( 8.0 \times 10^{-6} \) |
| Reference temperature (K)                       | \( T_R \) | \( 2.83 \times 10^{2} \) |
be similar from 6:00 p.m. on 8 September 2019 to 6:00 p.m. on 9 September 2019, and the peak temperature of the inner surface of the PCM-glazed unit with a 3-mm thickness of PCM was the highest. When the ambient temperature change was significant from 8:00 a.m. to 1:00 p.m., there is less fluctuation of the inner surface temperature. The main reason is that the PCM has a high latent heat of phase change, which delayed the change in internal surface temperature. When the ambient temperature decreased, the most obvious temperature decrease was that of the PCM-glazed unit with a 3-mm-thick PCM layer. The peak temperature and the temperature gradient after 14:00 of the test facility with different
PCM-layer thicknesses are given in Table 5. With PCM-layer thickness increasing, the temperature gradient decreases by 10% from 3.09 to 2.78, which indicates that the thermal storage capability of the PCM-glazed unit increases with PCM-layer thickness increasing. However, when the PCM-layer thickness exceeded 9 mm, the temperature gradient was relatively close, which means that although increasing the thickness of the paraffin can improve energy-saving glass structure, but the energy saving effect is not further increase significantly.

Figure 5 shows the experimental results of surface strains on the PCM-glazed units with different PCM-layer thicknesses at point 1. The experimental data show that compressive

Table 5. The measuring data and analysis of temperature.

| Thickness of PCM (mm) | Peak time | Peak value (°C) | Temperature gradient |
|-----------------------|-----------|-----------------|----------------------|
| 3                     | 12:30     | 37.2            | 3.09                 |
| 5                     | 12:30     | 35.9            | 2.95                 |
| 7                     | 12:30     | 35.6            | 2.91                 |
| 9                     | 12:30     | 34.4            | 2.8                  |
| 11                    | 12:30     | 33.9            | 2.78                 |

Figure 5. Measuring data of temperature and strain at point 1 (a: Inner horizontal, b: Inner longitudinal, c: Outer horizontal, d: Outer longitudinal).
strain occurs when the temperature is below 18 °C, i.e., the PCM phase-transition temperature, and tensile strain occurs when the temperature is above 18 °C. The strain components in the horizontal and longitudinal directions are different due to the PCM-glazed unit with dimensions of 400 mm × 500 mm (Height × Width). The horizontal strains are larger than the longitudinal strains on the inner surface of the PCM-glazed unit at point 1. The PCM-layer thickness has an important effect on the surface strain. It is also seen from Figure 5 that the strain on the inner surface of the PCM-glazed unit with PCM-layer thicknesses of 3 and 5 mm fluctuates greatly. The reason is that the PCM-layer thickness is too thin, and thus the heat-insulation effects of the PCM-glazed unit cannot be effectively improved. The variation trend of the inner surface temperature of the glazed units with different PCM-layer thicknesses is similar. The strain on the outer surface of the PCM-glazed unit with PCM-layer thicknesses of 9 and 11 mm fluctuates greatly. The reason is that the PCM layer is too thick to transfer the surface temperature quickly. The outer longitudinal peak strain on the surface of PCM-glazed units is larger than that of the horizontal peak strain, which is mainly due to the effects of the unfilled PCM, which results in a larger longitudinal temperature gradient. Among the five test facilities, the surface strains of the PCM-glazed unit with a PCM-layer thickness of 7 mm exhibit a small variation in each direction.

Figure 6 illustrates the measurement data of surface strains on the different points of a PCM-glazed unit with a PCM-layer thickness of 7 mm. As can be seen from the Figure 6, the variation trend of the strain difference between the outer and inner surfaces of the PCM-glazed unit is also obviously different. When the ambient temperature change is small during the night, the variation of the inner-surface strains of PCM-glazed units is slower than that of the outer-surface strains.

Surface stress distribution
In order to study the strain distribution at different positions of the glazed unit with PCM, the glazed unit had dimension of 0.5 m × 0.4 m (Width × Height) with 5 mm thickness of each glass layer. The material properties were presented in Table 4. Selecting the coldest January average temperature as the outdoor ambient temperature, which is about -20 °C. Indoor ambient temperature was set to 25 °C, which is a relatively comfortable temperature for the human body. The four sides of the PCM-glazed were fixed. The displacement of nodes at x = 0, x = 500, y = 0 and y = 400 in x-, y-, z- direction are 0 and adiabatic. PCM with a thickness of 7 mm and a height of 200 mm was used to calculate. Due to the thickness
of the glass plane was much smaller in size than the length and width, the strain in the Z-
Component of the strain was not considered in this study.”

Figure 7 shows the X-Component of the strain contour plot on the inner-surface of a
glazed unit filled with PCM. It can be seen from the Figure 7 that the strain distribution at
different positions of the glazed unit is quite different, and the strain at the edge is bigger
than the strain at the center. In order to analyze the strain distribution at different positions
more clearly, three analysis paths are chosen on the inner surface and the outer surface, one
of which is the strains in the middle Y along the X direction (X-path), and the other is
the strains in the middle X along the Y direction (Y-path) and the last is the strains of X
from 0 to 0.5, Y = 0.1 direction (X1-path), as shown in Figure 8. The X-Component of the
strains at different positions of the X-path and X1-path are shown in the Figure 9(a),
and the strains of the inner surface are greater than that of the outer surface of the corre-
sponding position, and the strains on the X1-path of the inner surface are greater than
those on the X-path. The Y-Component of the strains on the X1-path of the inner
surface are greater than that on the X-path within the range 83 mm from the edge, but
the Y-component of the strains on the X1-path on the inner surface at other locations are
smaller than those on the X-path. The strains at different positions of the Y-path are
shown in the Figure 9(b), which are same as along the X-direction, and the inner surface
strains along the Y-direction are greater than the outer surface strains. For the inner surface
strains, there is a significantly difference in the position with or without PCM. The reasons
as follows: (1) The glazed unit contains both PCM and air. They have different thermal
conductivity, which affect the temperature and the strain distribution of the glazed unit, and
the strains in the position without PCM are small. (2) The size of the glazed unit in the X-
direction is larger than that in the Y-direction, and the deformation in the X-direction is
large. (3) The boundary condition is set to 0, which has a great effect on the strain distri-
bution of the glazed unit filled with PCM, and the range of influence is 83 mm from the edge
in this study.
**Effect of PCM height**

To investigate the effect of PCM height on the surface strain of glazed units under large temperature difference, five glazed units with PCM heights of 200, 240, 280, 320, and 360 mm were studied, and other conditions were same as the Surface stress distribution section.

Figure 10 shows the X-Component strains on the inner surface of glazed units with different PCM heights on the X1-path and the Y-path. It can be seen from Figure 10 that the PCM height affects the surface thermal strain significantly. It can be seen from Figure 10(a) that in the range of 0Y-p mm from the edge on the X1-path, the X-component strains on the inner surface of the glazed unit increase with the increase of the PCM height, and the X-component strains of the other positions decrease with the increase of the PCM height. The X-component strains of the inner surface of the glazed unit of all kinds of PCM
height are close to 7.5E-5 at a distance of 83 mm from the edge. Figure 10(b) shows that the height of the PCM has a significant effect on the X-component strains on the inner surface of the glazed unit along the Y-path. However, the X-component strains are slightly affected by the height of the PCM at the edge.

Table 6 shows that the maximum strain on the surface of the glazed unit with the different PCM heights. When the PCM height in the glazed unit is 200 mm, the maximum tensile strain and the maximum compressive strain on the surface of the glazed unit are all small. In other words, with the increase of the height of PCM, the maximum tensile strain and the maximum compressive strain on the surface of the glazed unit have a significant increase.

Effect of size of exposed glazed unit

For investigating the effect of aspect ratios on thermal strain of PCM-glazed unit, the PCM-glazed units height of 400 mm and width of 400 mm, 500 mm, 600 mm, 700 mm, and 800 mm were investigated, namely, the aspect ratios of width are 1, 1.25, 1.5, 1.75, and 2, respectively. PCM-layer thickness of 7 mm and PCM-filling ratio of 0.8 were selected for simulation, and other conditions are the same as the Surface stress distribution section.

As shown in Figure 11, the characteristics of the influence of the aspect ratio of the glazed unit on the surface strain are different in the X1-path (X from 0 to W, Y = 0.1) and the
Y-path (X = 0.5 W, Y from 0 to 400 mm). Figure 11(a) shows that the aspect ratios of the glazed unit affect the surface thermal strain along the X1-path significantly. At the center position of the X-path, the strains of the glass structure increase with the increase in the aspect ratio, but the aspect ratios have a small effect on the edge strains of the glazed unit. It can be seen from Figure 11(b) that although the X-component strains on inner-surface of the glazed unit increase with the aspect ratios at the position away from the edge, the increase is less. The strains increase on the surface of the glazed unit filled without PCM is greater than those of the glazed unit filled with PCM.

From the Table 7, the maximum tensile strain \( (85.5 \times 10^{-6}) \) occurs when the aspect ratio of the PCM-glazed unit is 2, and the maximum compressive strain \( (-60.1 \times 10^{-6}) \) occurs when it is 1.75. The minimum tensile strain and minimum compressive strain are \( 76.1 \times 10^{-6} \) \( \varepsilon \) and \( -48.4 \times 10^{-6} \), respectively, which occur on the surface of the PCM-glazed unit with an aspect ratio of 1.5. Comparison of PCM-glazed units with different aspect ratios suggested that the PCM-glazed unit with an aspect ratio of 1.5 is safer in this study.

**Conclusions**

The main goals of present work are to discuss thermal performance and thermal strain distribution of PCM-glazed units by experimental and numerical simulations, in order to provide a reference for the design and application of PCM-glazed units in buildings. With the aim to investigate the thermal behavior of the glazed unit, the thicknesses of PCM,
heights of PCM, aspect ratios of the glazed unit were also studied. The following conclusions can be drawn:

1. The variation of thermal strain on surface of the glazed with a PCM-layer thickness of 7 mm is the smallest in five test facilities. In addition, the strain at the exposed edges of a PCM-glazed unit is greater than that at the center. The surface thermal strain always exhibits tensile strain when the temperature on the surface of the PCM-glazed unit is higher than the PCM’s phase-transition temperature, and when the surface temperature is lower than the phase-transition temperature of the PCM, the surface thermal strain always produces thermal compression strain.

2. PCM height plays an important role in the strain of PCM-containing glazed units is evident. With the increase of the height of PCM, the maximum tensile strain and the maximum compressive strain on the surface of the glazed unit increases significantly. Adding PCM to the glazed unit will increase the surface strain.

3. Regarding strains on the glazed units with different aspect ratios of glazed units, the minimum tensile strain and minimum compressive strain occurred at the aspect ratio of 1.5, which shows that it is safer for building applications.

This work expands the existing knowledge on PCM-glazed units by experiment and simulation. Future work should take into consideration the thermal stress distribution under extreme temperature and different methods of fixing PCM-glazed units.

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Appendix

Notation

c specific heat of PCM, J/(kg·K)
$C_{pg}$ specific heat, J/kg·K
E modulus of elasticity of glass, Pa
$f_l$ liquid fraction of paraffin undergoing phase change
$h_{out}$ convective heat transfer coefficient of the outer glass layer, W/(m²·K)
$I(s)$ the solar radiation intensity, W/m²
$k_g$ thermal conductivity, W/(m·K)
$k_p$ thermal conductivity of paraffin, W/(m·K)
$[K^{(e)}]$ the stiffness Matrix of element
$P_s^{(e)}$ the element load vector caused by surface stress
$P_i^{(e)}$ the element load vector caused by the initial stress
$P_b^{(e)}$ the unit load vector caused by the change in shape
$Q_L$ latent heat of PCM, J/kg
$S^r$ radiation source, W/m³
$T_g$ temperature, K
$T_{ref}$ reference temperature of the paraffin, K
$T_s$ melting temperature of paraffin, K
$T_l$ liquidus temperatures of paraffin, K
$T_{out}$ outer surface temperature of the outer insulation layer, K
$T_{a,out}$ ambient temperature, K
$T_{in}$ inner surface temperature of the glass facing indoor, K
$T_{a,in}$ indoor air temperature, K
$T_R$ reference temperature, K
$z$ Medium absorption coefficient, 1/m
$z_1$ the coefficient of thermal expansion of the material, /°C
$\beta$ the liquid fraction of PCM undergoing phase change.
$\varepsilon$ the strain
$\nu$ Poisson’s ratio
$\rho_g$ density of the glass, kg/m³
$\rho_p$ density of paraffin, kg/m³
$\sigma$ thickness, mm
$\sigma_b$ tensile strength, Pa
$\sigma_{bc}$ compressive strength, Pa
$\sigma_l$ the stress, Pa
$\tau$ time, s