Thermal Performance of Membrane Structures Integrated Phase Change Materials

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Abstract: The membrane structures, one of the typical large-span spatial structures, have been widely-used for sports stadiums and transportation hubs. However, the thermal performance of architectural membrane materials is not as good as those of the traditional building materials. The phase change material can absorb and release latent heat by changing its states within a very small range of temperature change, and thus reducing indoor temperature fluctuation and improving thermal comfort. In this paper, we proposed several membrane structural types to improve the thermal performance, including changing the single-layer membrane structure into two-layer, and setting air or phase change materials as the insulation layer in the middle. Temperature field simulations are performed based on COMSOL software to investigate the temperature variation and thermal performance of the membrane structures. The daily maximum temperature on the inner surface decreased by 2.1°C and 8.1°C respectively with air and PCM layer. We also discovered that the thermal insulation performance will be better when the latent heat value is higher and the PCM layer is placed nearer to the outdoor side. The temperature-stress coupling field showed the loss of pre-stress can be reduced by about 50% by adding PCM layer. The research results are believed to be significant for energy-saving and CO2 emission reduction in large public buildings.

Keywords: membrane structure, thermal resistance, COMSOL, phase change materials, numerical simulation

1 Introduction

Due to the advantages of light weight, self-cleaning, light transmittance and so on, membranes have been widely-used in the construction field in recent years, and many representative large-span buildings use membrane structures as roofing or envelope structures [1, 2]. However, compared with traditional building materials such as concrete, membrane materials are thin so the thermal resistance is quite small, and have weak buffering capacity on the indoor environment [3-5]. Moreover, the high transmittance of membrane will lead to high indoor temperature in summer [6]. Tian et el. [7] analyzed the thermal optical characteristic parameters of membrane samples and established a solar radiation heat transfer model. It is not easy to maintain the comfort and stability of the internal thermal environment in buildings with membrane structures as the external envelope [8]. Monitoring data show that under natural ventilation conditions, the overall thermal insulation performance of closed gymnasiums without thermal insulation design inside the membrane structure is poor, and their indoor thermal environment does not meet the basic requirements of thermal comfort [9, 10].

At the same time, the change of temperature can also cause additional thermal stress to the membrane materials, which affects their service life. Sun et al. [11] studied the thermal expansion performance and the thermal deformation performance of the ETFE membrane. Common means to improve the thermal performance of membrane structures include changing the single-layer membrane structure into a double-layer, combining it with an inflatable structure, using the good insulation capacity of the internal air layer to enhance the overall performance of the facility, or adding insulation materials between the double-layer membranes [12].

Phase change material can be used as insulation material to improve the thermal performance of the membrane structures, it is an energy-saving and environmental-friendly material, the thermal storage function is achieved by the energy change in the phase change period, the energy in the phase change materials can regulate the temperature effectively [13, 14]. The thermal insulation principle of composite phase change material is to store the outside temperature for thermal insulation of the building [15]. The high density of phase change materials makes it easier to control the temperature [12]. Zhu et al. [16] developed a dynamic heat transfer model of PCM Trombe room and conducted a simulation that showed a 13.52% reduction in the annual total building load. Wu et al. [17] proved the heat storage/release capacity of PCM is enhanced when it is placed closer to the outdoor side. This enhancement is closely related to the temperature distribution of PCM and its corresponding specific heat capacity. Saffari et al. [18] demonstrated that the use of PCM can reduce the thermal stress and the annual energy needs. Therefore, studies have shown that PCM can be used in building envelope as thermal insulation material, but there is little research on the possibility of using it to improve the thermal performance of membrane structures, so in this paper we proposed the idea of installing PCM layer in membrane structures and explore its feasibility.

In this paper, we proposed several membrane structures to improve the thermal performance, including changing the single-layer membrane structure into two-layer, and setting air or PCM as the insulation layer in the middle. Temperature fields based on COMSOL software were performed to investigate the temperature variation and thermal performance of the membrane structure under different boundary conditions. We also investigated the effect of latent heat value and the position of the PCM layer on its thermal insulation effect. Then the temperature-stress field coupling was continued based on the results of the temperature field, and the effect of the insulation layer on the thermal stress of the structure was obtained.

2 Simulation

2.1 Principle

2.1.1 COMSOL Multiphysics

Compared with other numerical simulation software, COMSOL Multiphysics has a complete multi-physics field coupling analysis capability, which is convenient for solving multi-physics field coupling problems. To accurately simulate and analyze actual equipment and processes, it is often necessary to consider the joint action of multiple physical fields. In the COMSOL Multiphysics software environment, users can flexibly couple multiple physical fields according to actual needs to achieve simulation analysis that is difficult or impossible to achieve through traditional methods. For example, in this study, the coupling between heat transfer and structural mechanics is needed to find the thermal stress caused by temperature changes.

The main modules used in this study are the heat transfer module and the structural mechanics module. All functions in the "Heat Transfer Module" are based on three modes of heat transfer: conduction, convection and radiation. Conduction in any material can have isotropic or anisotropic thermal conductivity, either as a constant or as a function of temperature. Convection, i.e., the movement of a fluid in a heat transfer simulation, can be either forced or free (natural) convection. In this study a combination of these three modes of heat transfer needs to be considered: heat conduction inside the membrane structure, thermal convection of air and the effect of solar radiation on the temperature of the membrane structure. COMSOL has the ability to handle different equations simultaneously to ensure the accuracy of the model.

Structural mechanics modeling options include 3D, 2D (plane stress, plane strain, and generalized plane strain), and 2D axial symmetry, and provide the most versatile method for analyzing structures with built-in multi-physics field coupling to a large number of physical domains. A variety of material models are provided to accurately describe solid mechanics problems, and these features can also be easily extended by equation-based modeling. By using constants, spatially varying expressions, anisotropic or nonlinear expressions, look-up tables, or a combination of all of the above.

2.1.2 Control Equations

Convective heat transfer occurs between the outer membrane and the external air and is simulated numerically using Newton's cooling theorem as follows:

$$-\mathbf{n} \cdot \left(-k \Delta T\right) = h\ (T_{ext} - T) \tag{1}$$

where k is the coefficient of thermal conductivity, ΔT is the temperature gradient, h is the coefficient of heat transfer, T_{ext} is the external temperature, T is the wall temperature.

In this problem, the main concern is the temperature change of the membrane structure, we don’t focus on the velocity and temperature of the external air involved in cooling or heating, and the heat transfer coefficient h does not change significantly along the boundary of the structure, so the heat transfer coefficient h can be simplified to a constant while calculating. When natural convection occurs between the gas and the wall, the heat transfer coefficient h = 2 to 25$W/(m^2 \cdot K)$, taking h as 20 $W/(m^2 \cdot K)$.

The heat transfer equation for the outer membrane also includes radiative heat transfer:

$$q = \epsilon\ (G - e_b(T)) \tag{2}$$

where ε is the surface emissivity, G is the irradiation, and $e_b(T)$ is the blackbody hemispherical total emissive power.

Heat transfer equation inside the membrane structure:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \Delta T + \Delta \mathbf{q} = Q \tag{3}$$

$$\mathbf{q} = -k \Delta T \tag{4}$$

where ρ is the density of the solid; p is the heat capacity of the solid at constant pressure; k is the thermal conductivity of the solid; and u is the velocity field of the partial model. q is the heat source. Add one or more heat sources as separate physical properties.

Changes in temperature lead to changes in stresses in the structure, and the equation for thermal expansion of the stress field under changes in temperature is calculated as:

$$\varepsilon_{th} = \alpha(T)(T - T_{ref}) \quad (5)$$

$$Q = Q_d = -T\frac{\partial(s:\alpha)}{\partial t} \quad (6)$$

where α is the coefficient of thermal expansion, T_{ref} is the volume reference temperature, and Q is the heat.

2.1.3 Phase Change Materials

Phase change materials regulate temperature by absorbing large amounts of heat while changing their own material state within a small range of temperature change. For the use of phase change materials in building insulation, the phase change temperature should be within the range of structural temperature change, and it is recommended to take the value of phase change temperature close to the human thermal comfort temperature in order to better achieve the effect of maintaining the thermal comfort of indoor environment. Hamidi et al. [19] analyzed that the optimal phase change temperature in Mediterranean region is 26°C. Guo et al. [20] found that the energy reduction efficiency of PCM layer is higher in warm climate zone than in cold climate zone. Since we need to consider the effect of thermal stress on the membrane structure, a summer climate condition in Shanghai was chosen for the simulation analysis, and the phase change temperature was selected as 36°C and the width of the melting zone as 6K.

It has been shown that the latent heat value and density of the phase change material have a large influence on its temperature regulation effect. In this paper, the influence of latent heat value on the temperature regulation effect is investigated. The "Heat Transfer Module" of COMSOL provides two different methods to simulate the phase change phenomenon in heat transfer analysis, among which the "Phase Change Material" feature is used to implement the apparent heat capacity equation and to analyze the change of phase change enthalpy and material properties.

2.2 Modeling Process

2.2.1 Materials

The materials considered in this paper are PTFE, PCM and air. Their basic physical parameters are summarized in Table 1.

Table 1 Basic physical and thermal properties of PTFE and PCM.

Material	Density [kg/m^3]	Thermal conductivity [W/(m·K)]	Specific heat capacity [J/(kg·K)]
PTFE	1700	0.10	1100
PCM	1000	Solid:0.21 Liquid:0.18	Solid:2200 Liquid:2000

air	1.29	0.0267	1000

The relationship between specific heat capacity and temperature of PCM is shown in Fig 1. The phase change process takes place between 33 and 39℃. When the temperature rises to 33℃, the PCM starts melting and absorbing heat, the heat absorbed during the process is the latent heat value of the PCM. The heat will be released when the temperature drops.

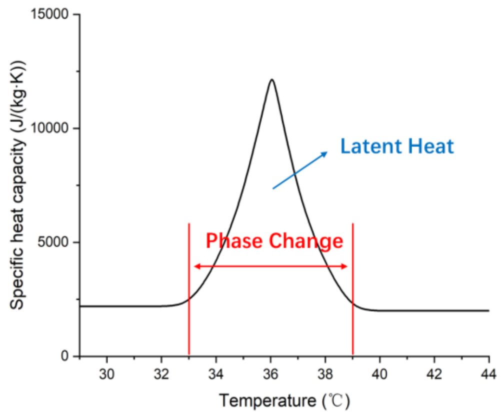

Fig.1. Specific heat capacity of PCM

2.2.2 Geometric features

When the influence of the structural form of the building on the thermal performance is not considered, the membrane structure can be simplified to two-dimensional conditions for simulation. The length of the structure is 0.5 m. The different configurations and the thickness of each layer are shown in Table 2.

Table 2 Different configurations of membrane structures.

Configurations	Layers from outdoor to indoor (type and thickness)	Total thickness [mm]
Single membrane layer	PTFE(2mm)	2
Double membrane layer with air layer in the middle	PTFE(2mm)+air(50mm) + PTFE(2mm)	54
Double membrane layer integrated PCM (PCM on the outdoor side)	PTFE(2mm) +PCM(10mm) +air(40mm) + PTFE(2mm)	54
Double membrane layer integrated PCM (PCM in the middle of air layer)	PTFE(2mm) +air(20mm) +PCM(10mm) +air(20mm) + PTFE(2mm)	54
Double membrane layer integrated PCM (PCM on the indoor side)	PTFE(2mm) +air(40mm) +PCM(10mm)+ PTFE(2mm)	54

However, the influence of the structural form on its thermal performance cannot be ignored in practical, for example, at the same moment, membranes placed in different angles are affected by solar radiation differently. Therefore, we take the typical hemispherical tensioned membrane structure shown in Fig 2 as an example for simulation.

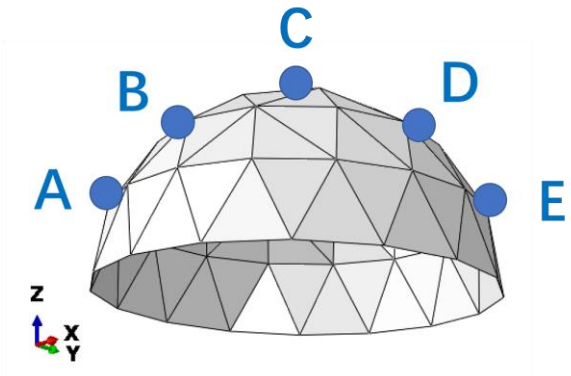

Fig.2. Numerical model of hemispherical tensioned membrane structure

2.2.3 Boundary Conditions

The temperature of the membrane structure is mainly influenced by ambient temperature and solar radiation, and the historical recorded values of Shanghai in summer shown in Fig 3 are used for simulation. As shown in Fig 4, the ambient temperature exchanges heat with the outer membrane through convective heat transfer while the solar radiation exchanging through radiant heat transfer.

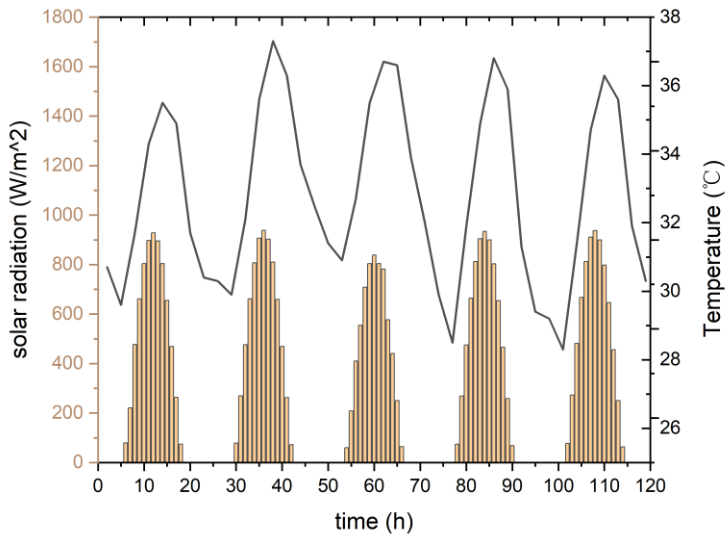

Fig.3. the historical recorded values of solar radiation and temperature

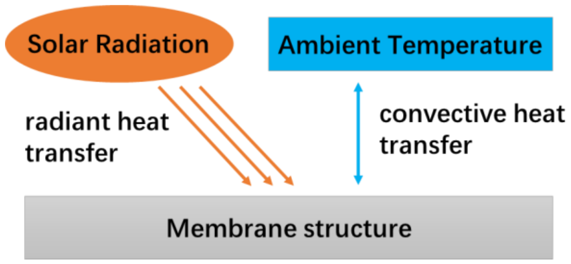

Fig.4. Schematic diagram of the boundary heat transfer conditions

3 Result and discussion

3.1 Temperature field

3.1.1 The effect of insulation

The temperature field of the single-layer membrane structure, the double-layer membrane structure with an air layer in the middle and a double-layer membrane structure with a PCM insulation layer added in the middle of it are simulated under the effect of ambient temperature and solar radiation. The one-day temperature curve at the inner surface of the membrane structure is shown in Fig 5. The maximum temperature at the inner surface for each configuration of membrane structures is shown and compared in Table 3.

The single-layer membrane structure had little buffering effect on the external environment, while after adding the air layer, its thermal insulation performance was significantly improved, and the daily maximum temperature on the inner surface decreased by 2.1°C on average, and there was a significant time lag. And after adding the phase change layer, the temperature curve showed an obvious plateau section near the phase change temperature, and there was no big fluctuation in one day time, indicating that the phase change material insulation layer has a strong role in maintaining the temperature stability.

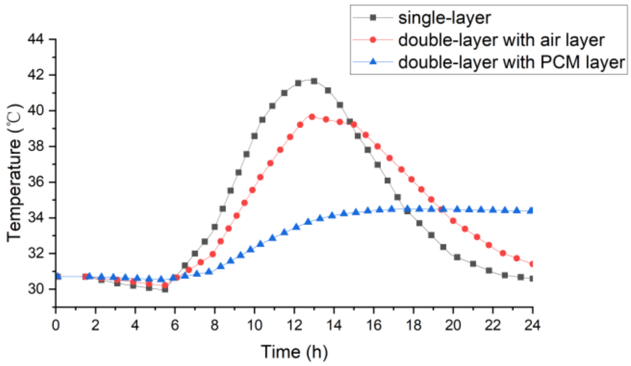

Fig.5. Temperature at the inner surface

Table 3 Single day maximum temperature at the inner surface and difference for different configurations of membrane structures.

Configurations	Maximum temperature at the inner surface (℃)						Difference with single-layer membrane structures(℃)					
	Day 1	Day 2	Day 3	Day 4	Day 5	Avg	Day 1	Day 2	Day 3	Day 4	Day 5	Avg
Single membrane layer	41.74	43.32	42.22	42.66	42.37	42.46	-	-	-	-	-	-
Double membrane layer with air layer in the middle	39.69	40.94	40.23	40.17	40.76	40.36	2.04	2.38	1.99	2.49	1.61	2.10
Double membrane layer integrated PCM	34.49	34.30	34.47	33.92	34.62	34.36	7.25	9.02	7.74	8.74	7.75	8.10

3.1.2 The effect of latent heat value

In order to evaluate the thermal insulation effect of the PCM layer more intuitively, an inward heat flux $q = 20W/m^2$ was set at the boundary. The temperature curves of the inner surface with different latent heat values (140-260 kJ/kg, taking the interval of 40 kJ/kg) were obtained as shown in Fig 6. At 0-5 hours, the PCM has not yet entered the phase change stage and relies on its specific heat capacity to regulate temperature. As a result, the curves remain basically the same and the latent heat value has no effect on temperature change during this time. When the latent heat value is 140, 180, 220, and 260 kJ/kg, the slope of the curve is 0.18, 0.12, 0.10, and 0.09 respectively. This means that the larger the latent heat value is, the smaller the slope of the curve will be and the slower the slope of temperature increase. This results in a longer time required to reach the temperature at the end of the phase change phase. In other words, the longer that PCM can maintain temperature stability during this phase. When the latent heat value is 140 kJ/kg, the phase change phase lasts for about 10 hours. When it reaches 260 kJ/kg, it can last for more than 20 hours. From these numerical analysis results, it is clear that latent heat value has a greater influence on PCM's ability to maintain temperature stability. The larger the latent heat value is, the longer PCM can maintain temperature stability provided that temperature change should be in a range including phase change temperature.

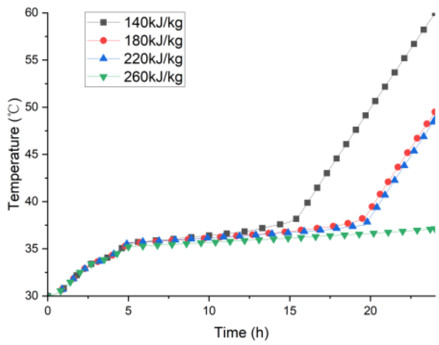

Fig.6. Temperature at the inner surface with different latent heat values

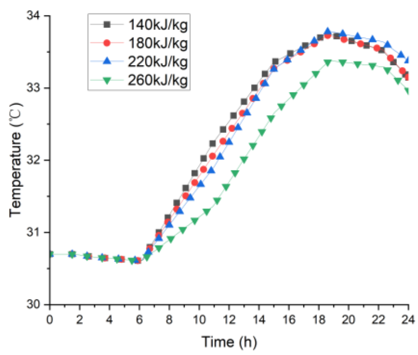

Fig.7. Temperature under the actual conditions

The temperature curves for different latent heat values under actual ambient temperature and solar radiation are shown in Fig 7. It can be seen that under actual conditions, latent heat value has a certain impact on the thermal insulation performance, but the impact is relatively small on a time scale of one day. It indicates that latent heat values above 140kJ/kg are sufficient to meet the temperature stability within one day under this weather condition. The influence of latent heat value will be more significant when the temperature exceeds the phase change temperature for a long time at high temperatures, and the heat absorbed during the phase change stage cannot be completely released at night.

3.1.3 The effect of PCM layer position

Similarly, an inward heat flux $q = 20W/m^2$ is set at the boundary, and the inner surface temperature curves are obtained for different PCM layer positions as shown in Fig 8. It can be seen that when the phase change material layer is placed near the outdoor location, the improvement of the overall thermal insulation performance of the structure is more obvious, but overall, the difference is small.

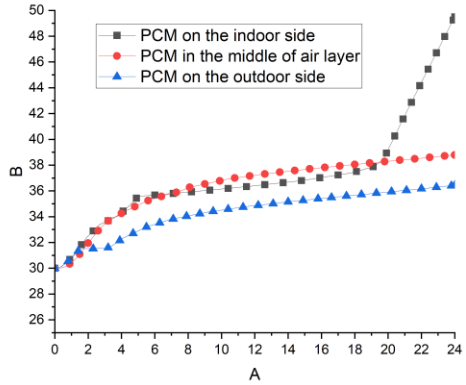

Fig.8. Temperature with different PCM layer positions

3.2 Temperature-stress coupling field

3.2.1 Two-dimensional model

The temperature-stress field coupling is continued based on the temperature field results obtained from the previous simulation. The PTFE membrane is hinged at both ends and the pre-stress is applied, the thermal stress results obtained from the simulation are shown in Fig 9. It can be seen that due to thermal expansion, the pre-stress on the membrane surface decreases from 1.8196MPa to 1.8174MPa under the effect of temperature, which is a decrease of 0.0022MPa, and there is an obvious loss of pre-stress, resulting in a decrease in the ability of the membrane to resist external loads, while the pre-stress only decreases to 1.81MPa after adding the PCM layer insulation, and the loss of pre-stress is reduced by about 50%, so adding PCM insulation layer can effectively relieve the generation of temperature stresses.

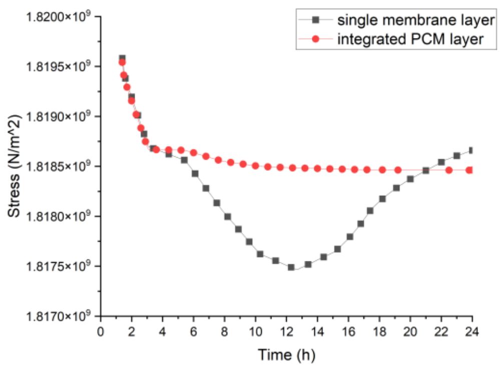

Fig.9. Thermal stress of membranes

3.2.1 Hemispherical tensioned membrane structure

The temperature field results of the hemispherical tensioned membrane structure are obtained from the simulation, and the temperature curves of some points are shown in Fig 10 and 11, the positions of the points are shown in Fig 2. According to the temperature field results, continue to carry out temperature-stress field coupling to get the thermal stress. Comparing with the two-dimensional thermal stress results, there is a certain difference in the temperature of each region of the structure, and the degree of loss of prestress is different, so it will cause additional stress to the structure. The effect of this part of stress can also be effectively reduced after adding the PCM layer insulation.

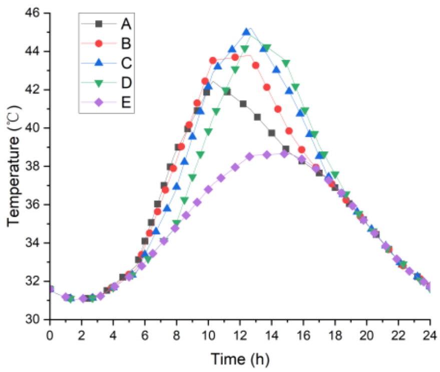

Fig.10. temperature of the single-layer hemispherical structure

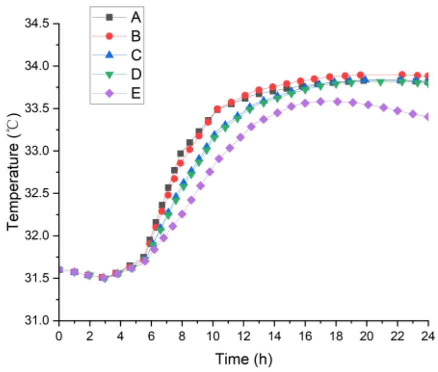

Fig.11. temperature of the hemispherical structure integrated PCM layer

4 Conclusion

In this study, simulations based on COMSOL software were carried out to calculate the temperature field of single-layer membrane, double-layer membrane structure with air layer in the middle and double-layer membrane structure integrated PCM insulation layer under the dynamic temperature action. Although the two-dimensional numerical results didn't take into account the influence of the structural form on the thermal performance, and therefore are still quite different from the results of membrane structures in practice, the simulation results can illustrate the improvement of the thermal performance by using different membrane structures.

Adding an air layer to the membrane structure has a significant improvement in the thermal performance, the daily maximum temperature on the inner surface decreased by 2.1°C on average, and there was a significant time lag, but it is still difficult to meet the needs of actual use. Therefore, it is necessary to add an insulation layer to significantly reduce the internal temperature variation and thus meet the basic need of maintaining a stable and comfortable thermal environment inside the building. After adding the phase change layer, the temperature curve showed an obvious plateau section near the phase change temperature, and the daily maximum temperature decreased by 8.1°C on average. For PCM as insulation materials, one of the most important material properties affecting the thermal performance of membrane structures is the latent heat value, the larger the latent heat value, the better the insulation effect. However, this is based on the premise that the phase change temperature is within the temperature variation range. Therefore, the value of the phase change temperature of the material should be analyzed according to the climate of the area where the actual building is located, and more in-depth research is still needed to use phase change materials as insulation materials. In addition, the position of the PCM layer also has an impact on its thermal insulation performance, the closer the PCM layer is to the outdoor side, the better the thermal insulation performance of the structure.

The temperature-stress coupling analysis is continued according to the simulation results of temperature field. It can be seen that the change of temperature will cause the membrane structure to produce certain pre-stress loss, which affects its ability to resist external load, and the difference of temperature in each region will also lead to stress generation, which has certain influence on the performance of membrane materials and service life. By adding the PCM layer as insulation, the loss of pre-stress can be reduced by about 50% Therefore, improving the thermal properties of membrane structures can also improve their mechanical properties and durability to a certain extent.

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References

[1] Hu J, Chen W, Qu Y, Yang D. Safety and serviceability of membrane buildings: a critical review on architectural, material and structural performance. Engineering Structures. 2020;210:110292.

[2] Hu J, Chen W, Yang D. Buildings with ETFE foils A review on material properties, architectural performance and structural behavior. Construction and Building Materials. 2017;131:411-22.

[3] Tian G, Fan Y, Gao M, Wang H, Zheng H, Liu J, et al. Indoor thermal environment of thin membrane structure Buildings: A review. Energy and Buildings. 2021;234.

[4] Hu J, Chen W, Qu Y, Yang D. Safety and serviceability of membrane buildings: A critical review on architectural, material and structural performance. Engineering Structures. 2020;210.

[5] Hu J, Kawaguchi K, Ma J. Long-term building thermal performance of enclosed large-span swimming stadiums with retractable membrane ceilings. Energy and Buildings. 2020;207:1-9.

[6] Hu J, Kawaguchi Ki, Ma J. Long-term building thermal performance of enclosed large-span swimming stadiums with retractable membrane ceilings. Energy and Buildings. 2020;207.

[7] Tian G, Fan Y, Wang H, Zheng H, Gao M, Liu J, et al. Studies on the thermal optical properties

and solar heat gain of thin membrane structure industrial building. Solar Energy. 2021;213:81-90.
[8] Kumar A, Suman BM. Experimental evaluation of insulation materials for walls and roofs and their impact on indoor thermal comfort under composite climate. Building and Environment. 2013;59:635-43.
[9] !!! INVALID CITATION !!! 6-8.
[10] Hu J, Chen W, Ren S, Zhang S, Qu Y, Yin Y, et al. Building performance monitoring and analysis of a large-span aerogel-membrane airport terminal. Engineering Structures. 2020;219:110837.
[11] Sun G, Wu M, Qu X, Xue S. Experimental investigation of the uniaxial tensile properties and thermal deformation of the ETFE membrane at different temperatures. Construction and Building Materials. 2022;327.
[12] Suo H, Angelotti A, Zanelli A. Thermal-physical behavior and energy performance of air-supported membranes for sports halls: A comparison among traditional and advanced building envelopes. Energy and Buildings. 2015;109:35-46.
[13] Hendricks J, Van Sark W. Annual performance enhancement of building integrated photovoltaic modules by applying phase change materials. Progress in Photovoltaics: Research and Applications. 2013;21:620-30.
[14] Ma T, Yang H, Zhang Y, Lu L, Wang X. Using phase change materials in photovoltaic systems for thermal regulation and electrical efficiency improvement: A review and outlook. Renewable and Sustainable Energy Reviews. 2015;43:1273-84.
[15] Khawaja SA, Memon SA. Novel indicators to evaluate PCM performance under different ventilation strategies by considering the impact of climate change. Journal of Building Engineering. 2023;74.
[16] Zhu N, Deng R, Hu P, Lei F, Xu L, Jiang Z. Coupling optimization study of key influencing factors on PCM trombe wall for year thermal management. Energy. 2021;236.
[17] Wu D, Rahim M, El Ganaoui M, Djedjig R, Bennacer R, Liu B. Experimental investigation on the hygrothermal behavior of a new multilayer building envelope integrating PCM with bio-based material. Building and Environment. 2021;201.
[18] Saffari M, Piselli C, de Gracia A, Pisello AL, Cotana F, Cabeza LF. Thermal stress reduction in cool roof membranes using phase change materials (PCM). Energy and Buildings. 2018;158:1097-105.
[19] Hamidi Y, Aketouane Z, Malha M, Bruneau D, Bah A, Goiffon R. Integrating PCM into hollow brick walls: Toward energy conservation in Mediterranean regions. Energy and Buildings. 2021;248.
[20] Guo J, Zhang G. Investigating the performance of the PCM-integrated building envelope on a seasonal basis. Journal of the Taiwan Institute of Chemical Engineers. 2021;124:91-7.