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Numerical Research on the Performance of a Phase Change Heat Storage Electric Heating Module

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Abstract. A kind of phase change heat storage electric heating modules filled with the composite PCM was designed and fabricated in this paper. The thermal performance of the module was studied through the experiments, and the thermal performance influencing factors were studied using the FLUENT software. Simulation results indicated that the optimal thermal conductivity of the PCM should be between 3 W/(m·K) and 5W/(m·K). With the designed arrangement of the heating wire, the optimal electric heating power should be between 9.00W/m and 9.85W/m, and the corresponding adjustments should be made according to the local electricity price policy. When the electric heating power is 9.85W/m and the thermal conductivity is 4W/(m·K), the distance between the heating wire should be between 40mm and 45mm, which can ensure the high heat-storage efficiency and heating continuity. In general, the internal temperature of the module is relatively uniform and can maintain stable heat dissipation within the effective heating range for a long time. The temperature fluctuation of the module heat dissipating surface is small. The module has good thermal performance and can meet the heating requirements when being applied to electric radiant heating in the building.

1 Introduction

In recent years, energy crisis and environmental issues have been widely concerned all over the world. Phase change heat storage electric heating as a new heating mode, combines electric heating with phase-change heat storage technology, has become a hotspot of research and application due to energy-saving and environment-friendly. In recent years, a lot of researches ([1–4]) showed that the combination of the PCM and the building enclosure can improve the room heating comfort, reduce the overall heating cost and the energy saving effect is very significant.

In this paper, $CaCl_2·6H_2O$/EG shape-stabilized composite PCM was prepared by melt blending method. A kind of phase change heat storage electric heating modules was designed and fabricated. The experiments and numerical simulation were carried out to study the effects of different factors on the thermal performance of the module, the optimum value range of each parameter was obtained.

The research results showed that the phase-change heat storage electric heating module can maintain stable heat dissipation for a long time. The module has good thermal performance, and the temperature fluctuation of the module surface was small, which is beneficial to improving the indoor thermal environment. This research demonstrates the great application potential of the phase change heat storage electric heating technology in building heating, and provides parametric experience for the design optimization and application of phase change thermal storage electric heating modules in the future.

2 Numerical model validation

2.1 Experiment description

2.1.1 Fabrication of the module

Fig.1 shows the internal structure diagram of the phase change heat storage electric heating module. 6061 Al alloy panel with a thickness of 1.5mm is selected to be pressed and welded into the module shell. The carbon fiber heating wire is selected as the heat source of the module, pre-arranged at a height of 2 cm in the cavity shell as shown in Fig.1. The proportion of shape-stabilized composite PCM is 88%$CaCl_2·6H_2O$+2% $SrCl_2·6H_2O$+88%10%EG. The PCM was filled into the shell in a molten state followed by appropriately compacting. Integrated material was formed after solidification and the module was obtained. The dimension of the model is 200mm × 200mm × 40 mm (length× width × height). The length of heating wire arranged in the module is 1m. In order to ensure the heating effect of the module and make the heat flow to the indoor environment as far as possible, heat preservation was provided on the periphery and the back of the module, and polyurethane foam was used to fill the gap at the edge.

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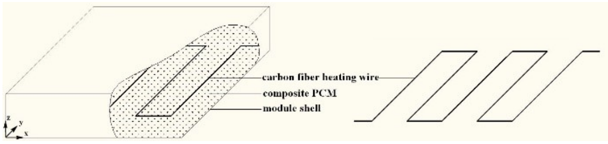

Fig. 1. The diagram of module structure.

2.1.2 Test point arrangement and instrumentation

A series of temperature and heat flux should be measured to investigate the thermal performance of the module. 2 thermocouples were arranged at the 3cm high position to test the average temperature of the whole module. And the temperature of the heating wire, the surface on the outside of the module and the indoor heat dissipation surface were also tested by thermocouples with accuracy of ±0.75%. In addition, a heat flux meter with accuracy of ±5%was attached to the outer surface of the module indoor side to test the variation law of the heat flux density of the module surface. The test was carried out in a standard chamber.

2.2 Numerical model description

2.2.1 Physical model development

In this paper, the enthalpy method was used to establish a mathematical model and a numerical simulation study was performed using the FLUENT software. The effects of the thermal conductivity, electric heating power and the distance between the heating wire on the heat storage and release performance of the module were investigated. Due to the structure and boundary conditions of the module both have the characteristic of symmetry, only one fifth of the module was taken for establishing the heat transfer model. Based on this, the three-dimensional heat transfer physical model of the heat-storage unit was established. The dimension is 200mm×40mm×40mm (length× width× height). A time control method was adopted on the module, with 24h as a thermal cycle including 8h heat storage and 16h heat release.

2.2.2 Governing equations

In order to simplify the mathematical model of heat transfer and facilitate calculation, the assumptions are listed as follows: (1) the physical properties (the density, specific heat capacity, thermal conductivity) of the materials are constant, and the super-cooling degree is ignored; (2) the influence of the natural flow of the PCM can be ignored, the heat transfer equation is simplified to a pure heat conduction equation; (3) the shell thickness of the unit is zero, the non-uniformity of the heating power of each section of the heating wire is ignored, and the heat flux is considered to be uniform and stable; (4) the contact surfaces are closely attached, the thermal contact resistance between the surfaces is ignored. According to the assumptions, the following governing equations were established as:

$$\rho \partial H/\partial t = k\nabla^2 T \quad (1)$$

$$H = c_p\,(T - T_s) \qquad T \le T_s \quad (2)$$

$$H = H_s + \Delta H_m\,(T - T_l)/(T_l - T_s) \qquad T_s < T < T_l \quad (3)$$

$$H = H_l + c_p\,(T - T_l) \qquad T \ge T_s \quad (4)$$

2.2.3 Initial conditions, boundary conditions and physical properties of module materials

For the surface of the heating wire, the boundary condition is constant heat-flux boundary condition as (5). For the heat dissipating surface on the indoor side of the module, the boundary condition is the third type of boundary condition as (6). The boundary conditions of the other walls are all adiabatic boundary condition as (7).

$$-k_{PCM}\,\partial T/\partial n = Q(\tau) \quad (5)$$

$$-k_{PCM}\,\partial T/\partial n = h(T - T_{in}) \quad (6)$$

$$-k_{PCM}\,\partial T/\partial n = 0 \quad (7)$$

h is the convective heat transfer coefficient of the surface on the indoor side of the module, which was set as 9W/(m·K) according to the experimental results. T_{in} is the indoor ambient temperature, constant at 19℃, also used as the initial temperature. And other physical parameters settings of the materials used in module, the density is 1008.96 kg/m^3, the specific heat capacity is 2.73 J/g·℃, the melting and freezing temperature is 29℃ and 28.5℃, the latent heat of phase change is 172.92J/g.

When the grid number is 201574 and 292762, the trends of temperature changes are very close, so the grid number was determined to be 201574 in subsequent simulations. The time step was set as 10s.

2.3 Comparison and analysis of experimental and simulation results

In order to quantitatively describe the simulation results more representatively and compare them with the experimental results, the average temperature of Z=30mm plane and Z=40mm plane corresponds to the average temperature of the module and the temperature of module heat dissipating surface respectively.

Fig.2 compares the experimental and simulation results of the heat flux of the heat dissipating surface when the electric power was 10.47W/m. The overall average relative error of the temperature is controlled within 8%, and the average relative error of the heat flux is controlled within 10%. The experimental and simulation results show a good consistency, indicating that the established simulation model has acceptable accuracy and reliability in predicting the thermal performance of the module. Therefore, this model can be used for the subsequent simulation study of the factors affecting the thermal characteristics of the module.

The thermal of the module is also analysed. The heat-storage process is divided into three obvious periods, preheating period, phase-change period and overheating period. During the preheating and the overheating period, the PCM absorbed sensible heat, and the temperature rose rapidly. In the phase-change period, due to the large phase-change latent heat of the PCM, the temperature rise slowed down although a large amount of heat was absorbed. In the overheating period of the heat release stage, the module releases heat rapidly accompanied by the decrease of heat flux. In the later solidification stage, the temperature of the heat dissipating surface can be maintained within the effective heating temperature range (higher than 25℃) for a long time. And the heat dissipation capacity is maintained between 70 W/m^2 and 80W/m^2, the module can provide heat for the room stably. That is an ideal performance for indoor heating.

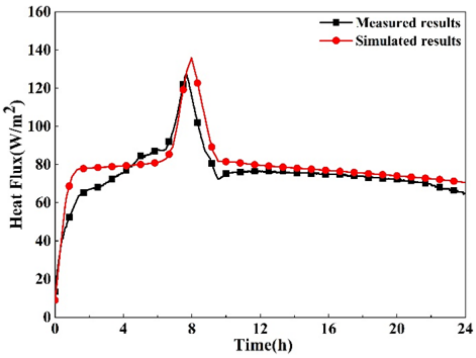

Fig. 2. Comparison between the heat flux curves.

3 Simulation results of the performance influencing factors

3.1 Effect of the thermal conductivity

Four different thermal conductivity values 1, 3, 5 and 7W/(m·K) were set respectively. The electric power of the heating wire was set to 10.3W/m. Fig.3 and 4 presents the curves of the heating wire temperature and the heat flux of the heat dissipating surface with different thermal conductivities. It can be seen that the local overheating phenomenon of the heating wire become more obvious as the thermal conductivity decreases. In the heat release stage, the heat dissipation with low thermal conductivity has an obvious decreasing tendency. When the thermal conductivity of PCM is lower than 3W/(m·K), improving the thermal conductivity has a good promotion on the stability of the heat dissipation effect. While, when the thermal conductivity of PCM increases to more than 3W/(m·K), the thermal conductivity can basically meet the internal heat transfer requirements in this temperature range, and the effect of continuing to increase the thermal conductivity is no longer obvious.

To sum up, considering the room heating effect and the overall heat transfer efficiency of the module comprehensively, the thermal conductivity of the module should be between 3 and 5W/(m·K) within the phase-change temperature range selected in this study.

3.2 Effect of the electric heating power

The electric power of the heating wire was set to 8.45, 8.80, 9.50, 9.85, 10.20 and 10.55W/m respectively. The thermal conductivity of the PCM was set to 4W/(m·K). The temperature and heat flux change curves of the heat-dissipating surface with different electric heating power are exhibited in Fig.5 and 6. It can be seen that the peak values of the temperature and heat flux continuously increased as the electric power increased under same heat storage time. When the electric power is lower than 9.50W/m, the module has not completed the overall melting process, which leads to a substantial reduction of the module temperature at the end of the heat release stage. When the electric power is higher than 9.85W/m, the overheating phenomenon caused by the increase of the electric power becomes more obvious, and the maximum overheating temperature is as high as 36.33°C, which greatly reduce the room thermal comfort ([5]).

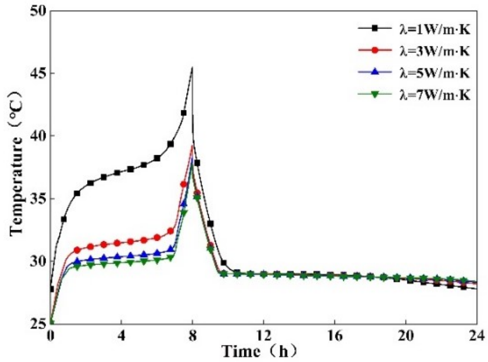

Fig. 3. Temperature of the heating wire.

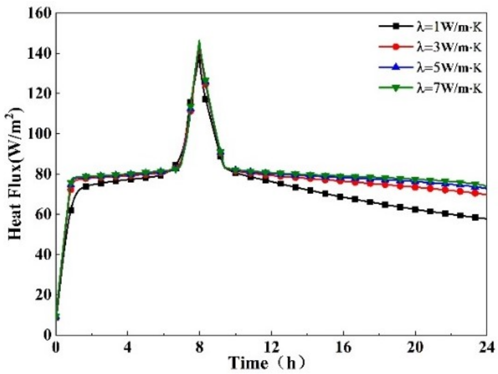

Fig.4. Heat flux of the heat-dissipating surface.

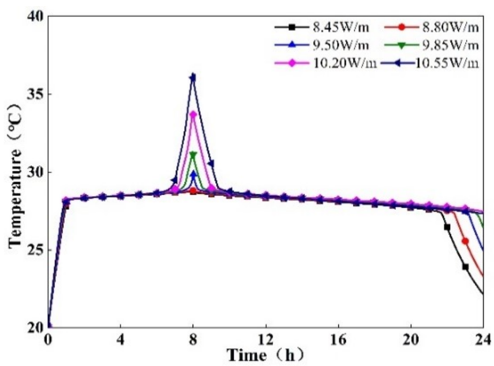

Fig.5. Temperature of the heat-dissipating surface.

To sum up, with the current arrangement of carbon fiber heating wire, the electric power of the heating wire should be between 9.00W/m and 9.85W/m with 8h heat storage. The electric power and the heat storage time can be adjusted according to the electricity price policy, and attention should be paid to avoid overheating of the module surface temperature.

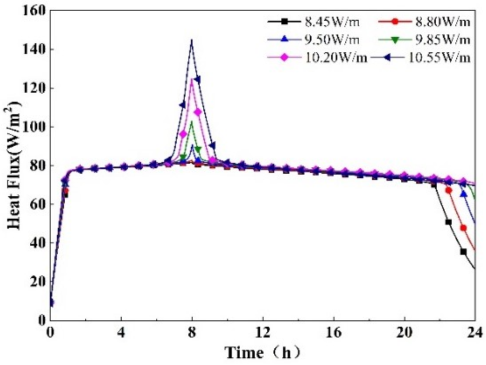

Fig.6. Heat flux of the heat-dissipating surface**.**

3.3 Effect of the distance between the wire heat source

The heating wire is arranged in a serpentine shape as shown in Fig.1. The distance between the heating wire affects the heat source density as well as the electric power, but the effect of the distance between the heating wire in the same direction on the temperature field is still unknown. To investigate the effect, the distance *d* between the heating wire in the same direction was set to 30, 35, 40, 45 and 50mm respectively. The thermal conductivity of the PCM was set to 4W/(m·K), and the electric power of the heating wire was set to 9.85W/m.

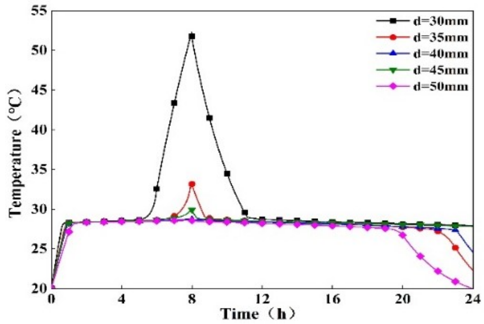

Fig.7. Temperature of the heat-dissipating surface.

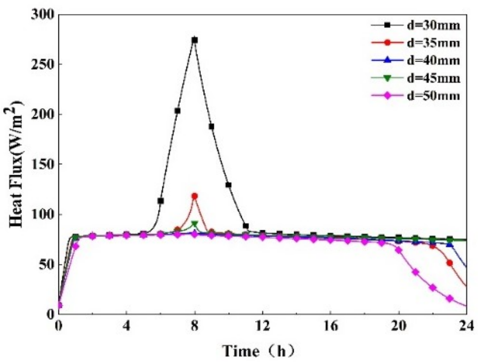

Fig.8. Heat flux of the heat-dissipating surface**.**

Fig.7 and 8 show the temperature and heat flux change curves of the heat-dissipating surface with different distances between the heating wire. It can be seen that when the heating wire is arranged too densely, the heat dissipating surface temperature is too high. When the distance *d* is 30mm, the surface temperature is as high as 52℃, which exceeds the temperature limit of floor radiant heating a lot and causes room heating discomfort. When the distance *d* is 40mm, the surface temperature and heat flux of the module are both relatively stable, which can maintain continuous heat dissipation during the entire heat cycle. While when the distance *d* is bigger than 45mm, the heat storage of the module is incomplete and insufficient, which caused that the heat dissipation is greatly reduced or even close to zero at the end of the heat release stage.

When the electric heating power is 9.85W/m and the thermal conductivity is 4W/(m·K), the optimal distance between the carbon fiber heating wire should be between 40mm and 45mm comprehensively considering heating continuity, comfort and the efficiency of the module.

4 Conclusion

The new type of phase-change heat storage electric heating modules proposed in this paper has good thermal performance, and the temperature field inside the module is uniform. The module can maintain stable heat dissipation within the effective heating range for a long time, which can meet the room heating requirements and it has good energy efficiency. The optimal thermal conductivity of the PCM filled in the module should be between 3W/(m·K) and 5W/(m·K). With the designed arrangement of the electric heating wire, the optimal electric heating power should be between 9.00W/m and 9.85W/m when the heat is stored for 8h. And when the electric heating power is 9.85W/m and the thermal conductivity is 4W/(m·K), the distance between the carbon fiber heating wire should be between 40mm and 45mm. This research provided parametric experience for the design optimization and application of the phase change heat storage electric heating modules in the future.

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