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Numerical Simulation of Effect of Inclination Angle on Heat Storage Properties of Phase Change Paraffin

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Abstract

In order to explore the heat storage properties of phase change paraffin, a calculation model for melting heat storage of phase change paraffin was established based on the equivalent heat capacity method. A finite element software (COMSOL) was used to study the influence of different inclination angles on heat storage properties of phase change paraffin. The results show that the melting process of phase change paraffin is determined by heat conduction and natural convection heat transfer, natural convection heat transfer plays a significant role in the process of heat storage in phase change paraffin. Phase change paraffin exhibits distinct melting heat storage efficiency under different inclination angles. When θ changes from -90° to 90°, the melting time of paraffin decreases gradually. When θ-90°, the melting time of paraffin is the slowest, when θ-90°, the melting time of paraffin is the fastest, and the melting speed of paraffin is increased by about 8.6 times.

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Introduction

Energy is an important material basis for the survival and progress of human society. With the deepening of social industrialization and the exponential growth of population, the human society is increasingly dependent on energy, and the excessive and rapid consumption of energy is one of the problems that the society needs to solve urgently.[1] The rapid consumption of non-renewable energy sources such as coal, oil and natural gas also leads to the greenhouse effect and air pollution. The development of new energy sources and the development of new energy-saving and consumption-reducing measures are effective means of alleviating the energy crisis. The emergence of phase change materials has provided a new research idea to solve this problem. Phase change material (PCM) is a material that can store or release a lot of heat during a solid-liquid phase change process while maintaining a constant temperature.[2-4] In this way, the imbalance between energy conversion, transportation and supply and demand can be solved so as to make better use of energy.[5] Compared with traditional sensible heat storage materials, phase change materials based on latent heat storage have higher heat storage performance. Paraffin, as a common organic

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phase change material, has been widely concerned because of its advantages such as wide phase change temperature range, large latent heat of phase change, good heat storage stability, low price and non-corrosive.[6-8] It is widely used in building energy saving, solar thermal power generation, cooling of electronic devices and other fields.[9-11]

The real phase change of paraffin melting and heat storage is an extremely complex process, including heat conduction, phase change and natural convection of liquid, sinking movement of solid phase, etc.[12,13] Therefore, a full understanding of the heat transfer process during melting is essential to improve the efficiency of the phase change. At present, scholars have explored and studied this process through experiments and numerical simulation. Korti A.I.N. and Guellil H.[14] experimentally investigated the effect of inclination angle on the thermal behavior during the melting of PCM in a square cavity. The results show that the inclination angle of the phase change material caused by the natural convective behavior driven by buoyancy has a significant effect on the transient melting process of the phase change material. The natural convection at the bottom is stronger and the global average Nusselt number increases by about 10% and 21% for strong convection compared to the inclined and vertical cases, respectively. Bondareva N.S. *et al.*[15] numerically analyzed the complex effects of system inclination and nanoparticle concentration on the paraffin melting process under natural convection conditions, and obtained the local and overall characteristics of the paraffin melting process of the system at different heating levels. Yang X.H. *et al.*[16] found through experiments that the inclination angle has a great influence on the formation and development of natural convection during the melting of pure phase change materials, and the complete melting time is reduced by 12.28%, 22.81% and 34.21% at 0°, 30° and 60°, respectively, compared with that at 90°. Allen M.J. *et al.*.[17] have analyzed the effect of the system inclination angle (0°~ 90°) on the melting and solidification of the phase change material in the cylindrical enclosure by experiment. It is found that the presence of natural convection during melting may significantly alter the liquid fraction of systems without foam or foil. Zennouhi H. *et al.*[18] conducted numerical simulations of the melting process within rectangular enclosures at different inclination angles. The effects of the inclination angle on the flow structure and heat transfer characteristics were investigated in detail. Joneidi M.H. *et al.*[19] investigated the effects of heat flux and inclination angle variations (0°, 45°, 90°) on rectangular cavity-containing PCM. The experimental results showed that with increasing heat flux, the main heat transfer mechanism is natural convection.

In this paper, the melting heat storage performance of phase change paraffin in square cavity was numerically simulated. Based on the equivalent heat capacity method, finite element software (COMSOL) was used to establish the heat storage calculation model of phase change paraffin. The evolution pattern of solid-liquid phase interface and heat storage properties during the melting of phase change paraffin by different inclination angles were investigated. The heat transfer mechanisms in the melting process of phase change paraffin were clarified. It provides a theoretical basis for the rational use of convective heat transfer effect and the improvement of phase change efficiency in the subsequent phase change heat storage design.

Computational Models and Boundary Conditions

The size of the physical model in this paper is a square with side length and it is completely filled with paraffin. The thermal physical properties of phase change paraffin are shown in Table 1. The heat source is a constant temperature T_w=50° C applied to the wall, and the other boundaries are adiabatic. The initial temperature is set to 15°. The heat transfer characteristics of phase change paraffin in different inclination angles were studied by changing θ, θ range-90,90.

Table 1: Thermal physical properties of phase change paraffin

Property	Paraffin
Melting temperature T_m (K)	298.15
Density p (kg/m^3)	849.7
Specific heat c (J/kg·K)	3220
Thermal conductivity k (W/m·K)	0.232
Dynamic viscosity μ (Pa·s)	0.00579
Thermal expansion coefficient α (K^{-1})	0.001

In simulating the melting process of paraffin, the following hypothesis is proposed.

(a) paraffin is homogenous and isotropic;(b) the mixed phase parameter between solid and liquid is a linear function of temperature;(c) liquid-phase incompressibility.

Based on the hypothesis, the governing equation of melting heat storage process of phase change paraffin was simplified.

Continuity Equations

$$\nabla \cdot u = 0 \quad ...(1)$$

Momentum Equations

$$\rho \frac{\partial u}{\partial t} + \rho(\nabla \cdot u)u = -\nabla p + \mu \nabla^2 u + F \quad ...(2)$$

Energy Equation

$$c\frac{\partial T}{\partial t} + \rho C u \cdot \nabla T = \nabla \cdot (k \nabla T) \quad ...(3)$$

Where *p, c, k, P, F* and *μ* is the density, specific heat capacity, thermal conductivity, pressure field, volume force vector and dynamic viscosity of paraffin, respectively. T is the temperature field.

In order to ensure the stability of the calculation during phase transition analysis, assuming that the phase transition occurs in a very small temperature range [T_S, T_l], the temperature range ΔT_l - T_s is generally 1K.

$$f = \begin{cases} 0 & T < T_s \\ (T - T_S)/(T_l - T_S) & T_s \leq T < T_l \\ 1 & T > T_l \end{cases} \quad ...(4)$$

The volume force F in the momentum equation (2) is given by temperature gradient caused by density differences. Satisfy the Boussinesq hypothesis, F can be described as follows

$$F = -\rho\left[1 - \alpha\left(T - T_{ref}\right)\right]g \quad ...(5)$$

Where T_{ref}, α and g is the melting temperature, thermal expansion coefficient and acceleration of gravity, respectively.

Based on the above assumptions, the relationship between dynamic viscosity *μ* and liquid fraction *f* is as follows

$$\mu = \mu_l\left[1 + \frac{C(1-f)^2}{\delta + f^3}\right] \quad ...(6)$$

Where the constant coefficients C and δ are usually equal to 10^5 and 10^{-3}, respectively.

According to equation (1)- (3), the effective thermal conductivity k, the effective density *p* and the effective specific heat capacity c can respectively be given by the following

$$k = (1-f)k_s + fk_l \quad ...(7)$$

$$\rho = (1-f)\rho_s + f\rho_l \quad ...(8)$$

$$c = \frac{1}{\rho}[(1-f)\rho_s c_s + f\rho_l c_l] + L_m \frac{d\beta}{dT} \quad ...(9)$$

Where c_s and c_l represent the solid and liquid specific heat capacities, respectively.

β can be expressed as follows

$$\beta = \frac{f\rho_l - (1-f)\rho_s}{2\rho} \quad ...(10)$$

Results and Discussions

Melting Temperature of Paraffin

Fig. 1 shows the variation of paraffin melting temperature at different inclination angles at different moments. As can be seen from Fig. 1, with the increase of heating time, the melting of paraffin with different inclination angles was gradually accelerated. At the same time, when the inclination angle θ changes from -90° to 90°, the melting efficiency of paraffin increases. This is because when θ= 90°, heat is transferred to the inside of the paraffin mainly by heat conduction, forming a melting edge essentially parallel to the heating surface. At this time, the natural convective heat transfer effect of paraffin can be ignored. When θ rotates from -90° to 90°, the natural convection is gradually strengthened, at which time the liquid paraffin in the melting layer moves upward under the action of buoyancy force and forms a tiny circulation at the apex. Subsequently, the hot liquid paraffin at the top will sink along the melting surface to the bottom, creating a large circulation in the liquid phase region and accelerating the melting of the paraffin. When θ continues rotating to 90°, the natural convective heat transfer effect of the liquid phase is fully activated due to the direction of the heat source is the same as that of buoyance force, forming a mushroom-shaped plume with a large influence range. As the time goes by, the mushroom-shaped plume gradually disappears and eventually forms a large circulation, at which time the melting heat storage efficiency of phase change paraffin reaches its maximum.

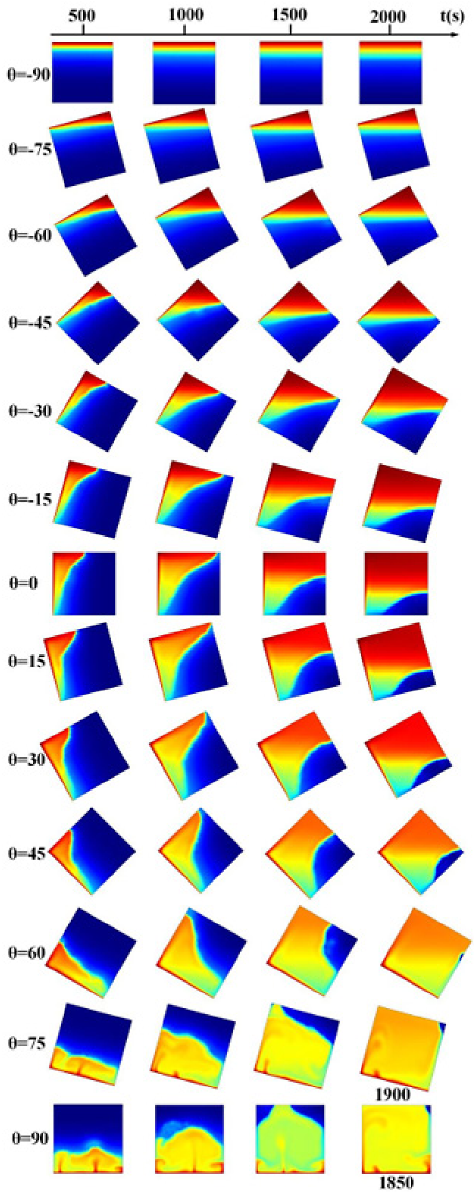

Fig. 1: Melting temperature of paraffin at different inclination angles at different times

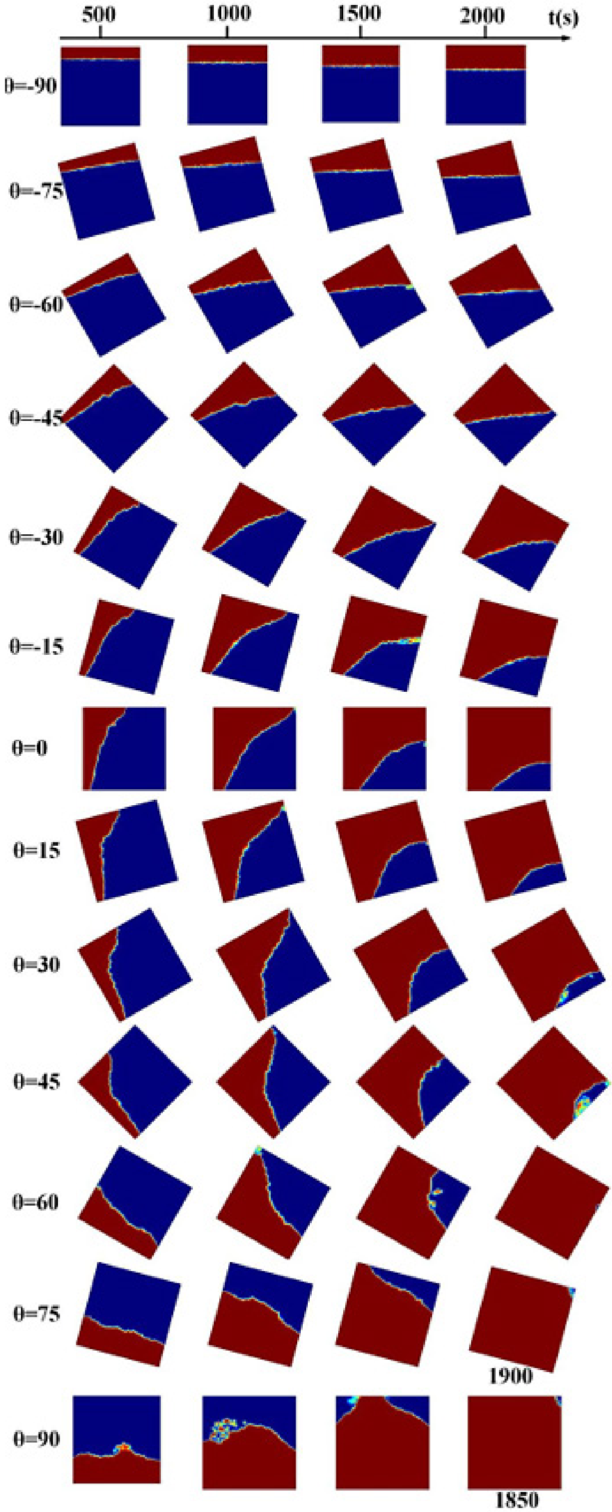

Fig.2: Paraffin melting fronts at different inclination angles at different times

Propagation of Paraffin Melting Front

To further demonstrate the unique melting behavior of phase change paraffin. Fig. 2 shows the changes of paraffin melting liquid level at different inclination angles at different times. According to the Fig. 2, phase change paraffin exhibits the distinctly different melting fronts at different inclination angles. When θ= 90°, the melting of paraffin is mainly affected by heat conduction, and natural convection is completely suppressed in liquid paraffin. Forming a melting front parallel to the heating surface. The resulting melting surface remains level and moves downward until the paraffin is completely melted, at which point the paraffin melting efficiency is at its lowest. When θ rotates from -90° to 90°, the liquid paraffin inside the melting layer moves upward under the buoyancy force. Then, the hot liquid paraffin in the top part sinks along the melting surface to the bottom, accelerating the melting of the paraffin. Under the continuous effect of natural convective heat transfer, the melting surface becomes more and more inclined. It can be seen that the natural convection heat transfer effect plays an extremely obvious role in promoting the heat storage process of paraffin melting. Continuing to rotate to 90°, the direction of the heat source is parallel to the direction of heat transfer, but opposite to the direction of gravity. Influenced by natural convection, the melting front of paraffin becomes wavy. With the increase of heating time, the melting efficiency of paraffin is the highest.

Opposite Paraffin Melting Temperature

In order to analyze the heat storage properties of phase change paraffin, Fig. 3 shows the variation curve of paraffin melting temperature with time at a constant temperature of T_w =50°C for different inclination angles on the opposite side. It can be seen that with the increase of heating time, the temperature of phase change paraffin in different inclination angles gradually increased and eventually tends to be stable. Heat conduction plays a major role in the initial stage of heating, and changing the Angle has little effect on the temperature of paraffin. After 2500s, the phase change paraffin with different inclination angles all warmed up in different ways. This is because as the heating time increases, the natural convection effect increases and destroys the dominance of heat conduction.

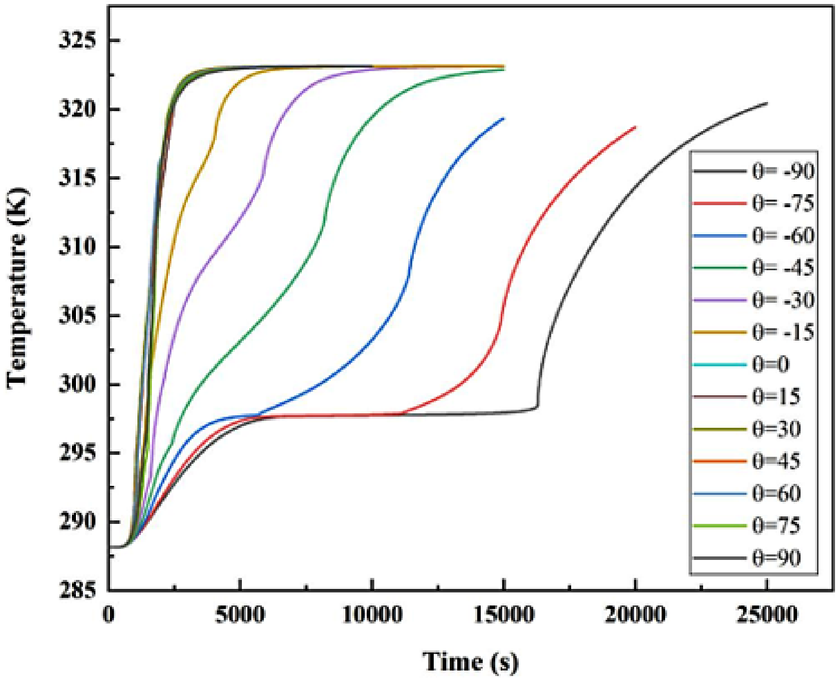

Fig. 3: Curve of melting temperature of opposite paraffin with time

Liquid Fraction

In order to investigate the effect of inclination angle on the phase change process of paraffin. Fig. 4 shows the variation of phase change paraffin fraction with time for different inclination angle. With the increase of heating time, the liquid phase fraction of phase change paraffin gradually increased at different inclination angles. When the phase change paraffin is completely melted, the liquid phase fraction reaches 1. When θ from -90° to 0°, the liquid phase fraction of phase change paraffin varies slightly under different inclination angles. This is due to the predominance of phase change paraffin thermal conductivity at θ= 90°, where the effect of natural convection can be ignored. When θ increases from 0° to 90°, the liquid phase fraction of phase change paraffin differs greatly under different inclination angles. When, since the direction of the heat source is the same as the direction of the buoyancy force. The natural convective heat transfer effect of the liquid phase is fully activated, when the melting heat storage efficiency of the phase change paraffin reaches its maximum.

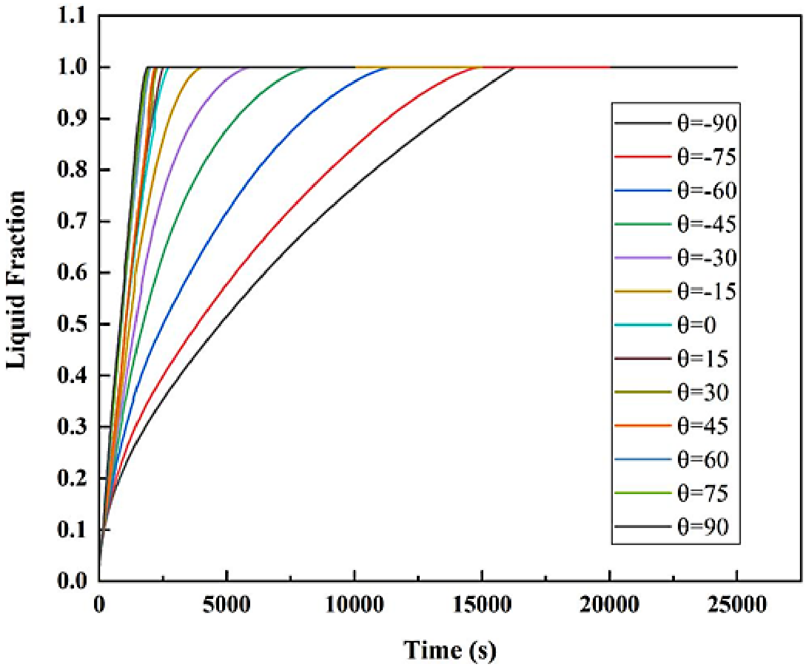

Fig. 4: Curve of melt liquid fraction of paraffin at different inclination angles with time

Final Melting Time of Paraffin

Fig. 5 shows the variation of the final melting time and inclination angle of paraffin. It can be seen that, as θ rotates from -90° to 90°, the paraffin melting time is gradually accelerated. When θ= 90°, the heat transfer within paraffin is dominated by heat conduction. At this time, the paraffin melted slowly, with a maximum melting time of 16310s. When changes from -90° to 0°, the natural convection heat transfer effect plays an extremely obvious role in promoting the heating and melting heat storage process of paraffin, which makes the melting efficiency of paraffin increase significantly. At θ=θ°, the paraffin melts completely at 2750s, which is about 5.9 times faster than -90° for the whole melting rate. As θ increases the inclination angle from 0° to 90°, the rate of paraffin melting increases slowly. However, at θ= 90°, the paraffin melted the fastest, with a melting time of 1890 s. At this point, the paraffin melting speed was increased by about 8.6 times.

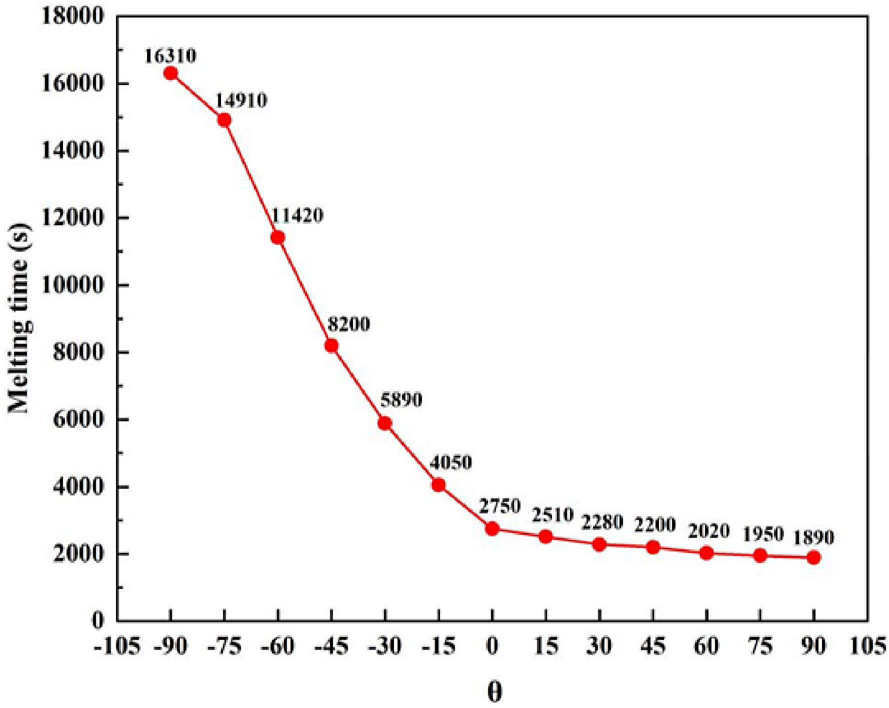

Fig. 5: The final melting time of paraffin varies with different inclination angles

Conclusions

Aiming at the melting and heat storage of phase change paraffin in square cavity, heat transfer characteristics of pure paraffin in different inclination angle were investigated by numerical simulation. The following major results conclusions were obtained.

(1) The heat storage process of phase change paraffin melting is determined by a combination of heat conduction and natural convection heat transfer, and natural convection plays an extremely significant role in promoting the heat storage process of phase change paraffin melting in the square cavity.

(2) The melting process of paraffin varies greatly under different inclination angles. The paraffin melting caused by bottom and side heating was significantly faster than the top at the same heating time. This is mainly due to the effects of natural convection. Compared to θ= 90°, the rate of paraffin melting is increased by about 8.6 times at θ= 90.

(3) Since the degree of performance of the buoyancy force is directly related to the direction of the heat source, it makes significant differences in the melting surface of phase change paraffin under the heat source in different directions, showing distinct melting and heat storage properties.

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Conflict of Interest

The authors declare no conflict of interest in this work.

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