Numerical study of nano-particle composite paraffin phase change heat storage capsule

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Abstract—The heat exchange characteristics of traditional heat exchange fluids such as water and oil in phase change heat storage can no longer meet the ever-increasing heat exchange requirements. The researchers found that by adding nano-scale particles to the basic phase change material (pure PCM) in a certain proportion to form a composite phase change material, the heat transfer characteristics of the material can be improved. In this paper, a model study of the phase change heat storage characteristics of the nano-particle composite paraffin wax phase change capsule with holes is carried out, and the effects of thermal disturbance, natural convection heat transfer and external convection heat transfer on the phase change heat storage are mainly studied. It is found that when nanoparticles are added to the phase change heat storage capsule, the composite phase change heat storage capsule formed by the phase change heat storage, the internal natural convection intensity increases, and with the increase of the particle share, the heat storage rate increases, and the heat exchange intensity increases.

1. Introduction

As researchers have further matured the research on the energy that can be continuously generated by nature such as the sun, everyone is more and more concerned about how to actually use these continuously generated energy. Yongqiang Liu[1] qualitatively analyzed the influence of the temperature and velocity of the heat exchange fluid on the phase change heat storage through the cloud diagram obtained by numerical simulation. It was found that when the flow rate and temperature of the heat exchange fluid are increased, the natural convection and heat storage inside the phase change material can be strengthened to a great extent. Wei Lu[2] et al focused on the changes in the density, viscosity, specific heat, etc. of composite materials with the particle share, and made detailed descriptions of the classic thermal conductivity model, the main production methods of composite nanomaterials and their existing problems. Qiang Li[3] further studied the Brownian motion of nanoparticles in composite materials based on the classic model. Wongwises[4] and others used experimental hot-wire methods to conduct experiments and measured the thermal conductivity and viscosity of composite materials. As a result, it is found that the thermal conductivity of the composite material is greatly increased relative to the basic material, and the viscous resistance of the particles will also increase.

So far, although many scholars have done in-depth research on the overall phase change thermal storage capsule. However, there are few researches on adding high thermal conductivity nanoparticles to the basic phase change material heat storage capsule to form a composite phase change material to change the performance of the phase change material, thereby enhancing the phase change heat storage.
2. Composite material phase change capsule model

This model uses the organic phase change material paraffin wax (RT44) as the heat storage material, and its melting temperature is 44 °C. It is known from the literature that the carbon nano-particles at a lower proportion have little effect on the phase change temperature and can be ignored. The latent heat of phase change is 250,000 J/kg. For the dynamic viscosity of water at the flow temperature, the value is 0.00035635 kg·(m³·s)⁻¹ according to reference. In this model, the flow rate of the heat exchange fluid is 1.2 m/s, the initial temperature is 350 °C, and the initial temperature of the phase change material is 313 °C. It only compares the difference in the phase change rate caused by the addition of nanoparticles with different physical properties. The phase change heat storage model used in this paper is designed based on the visual experiment of the foreign researcher GROY T and others with the heat storage packaging container with a cavity above. The heat storage capsule radius is 38.1 mm (The void volume accounts for about 10.2%). As shown in Figure 1:

![Physical model of a composite phase change capsule with holes](image)

3. Selection of basic phase change materials

The basic phase change material used in this article is RT44. In order to simulate the phase change process of melting and solidification, the physical parameters are provided by its manufacturer. As shown in Table 1, its melting temperature is between 42 and 45 °C, and its volume expansion coefficient is 0.008 (1/k). This model selects stainless steel as the material of the outer wall of the phase change heat storage capsule, and the heat exchange fluid selected is water.

| Material    | ρ (kg·m⁻³) | k (W·m⁻¹·K⁻¹) | Cp (J·kg⁻¹·K⁻¹) | L (KJ·kg⁻¹) |
|-------------|------------|---------------|-----------------|-------------|
| RT44        | 770 (l)    | 0.2           | -               | 250         |
| Water (350 K) | 880 (s)   | 0.2           | -               |             |
| steel       | 971.8      | 0.6           | 4195            |             |
|             | 8030       | 16.27         | 502.48          |             |

4. Simulation results and analysis

4.1. Model argument

In order to verify the validity of the model and the feasibility of setting the material properties, the model is set up in accordance with the literature, and the simulated solidification process is analyzed. As shown in Figure 2, from the apparent point of view, at 600 s and 1500 s, the model simulation method in this paper can be well in line with the actual simulation results, so the phase change analysis method of the composite paraffin wax phase change capsule in this article has a certain degree of reliability. When setting in FLUENT, the residual error of the energy equation is less than 10⁻⁶, and the residual error of the continuity and momentum equations is less than 10⁻³. The selected time step is 0.001 s, and the number of grids is 243059.
4.2. Analysis of flow field inside graphite/paraffin composite phase change capsule

Figure 3 shows the streamline diagrams of the graphite particle composite paraffin phase change capsules. The figure shows the intensity of thermal disturbance in the melted material during the melting of the composite phase-change heat storage material inside the capsule. At first, due to the high wall temperature, under the combined action of gravity and buoyancy, the melted liquid of the composite phase change material close to the wall rises along the wall, and then under the action of its own gravity, it rises again. When it falls, it will convectively exchange heat with the unmelted composite phase change material, thereby increasing the melting speed. When graphite nanoparticles are added, the flow lines of the internal flow field of the composite phase change material increase during the melting process, and the disturbance is strengthened. It shows that the addition of graphite particles makes the internal structure of the composite phase change material easier to melt, and during the melting process, the Brownian motion of the nanoparticles enhances the internal flow disturbance. The particle motion further strengthens the thermal disturbance of the melting process, which increases the streamline in the same time.

Fig.3 Streamline diagrams of graphite/paraffin composite phase change materials with different proportions of 0, 0.85%, 1.25%, 1.75% at different times
4.3. Analysis of heat transfer inside graphite/paraffin composite phase change capsule

Figure 4 shows the velocity vector diagrams of the composite paraffin phase change capsules. It can be seen from the figure that as the graphite nanoparticles are added to the basic phase change material and the volume share of the nanoparticles increases, the unsteady natural convection heat transfer increases and the melting process is accelerated. The addition of graphite particles changes the structure of the composite phase change material and strengthens its thermophysical properties. When the composite phase change material melts, more graphite particles can perform random Brownian motion, which strengthens the interaction between the graphite particles in the composite phase change material and the surrounding molecules. As time increases, the viscosity of the basic phase change material decreases and its temperature increases, which makes the Brownian motion of the graphite particles more intense and strengthens natural convection.

4.4. Analysis of Convection Heat Transfer Outside Graphite/Paraffin Composite Phase Change Capsule

Figure 5 shows that the convective heat transfer coefficient of the graphite/paraffin composite phase change heat storage material can be expressed as the composite phase change material in different proportions. The relationship between Nusselt number (Nu) and Reynolds number (Re). The Nusselt number in this paper is calculated at the 0° point of the capsule. The Nusselt number (Nu) and Reynolds number (Re) of composite phase change materials can be obtained according to the literature\cite{7,8}.

The convective heat transfer coefficient of graphite/paraffin composite phase change heat storage material is:

\[ h_0 = -k_w \frac{dT}{dr} \cdot \frac{1}{T_w - T_v} \]  \hspace{1cm} (1)

Where: \( h_0 \)— local convective heat transfer coefficient, W/(m²·K)
\( \theta \) is the sphericity measured from the stagnation point:

\[ Nu_\theta = \frac{h_\theta d}{k_f} = - \frac{k_f D}{k_f (T_w - T_v)} \frac{dT}{dr} \]  \hspace{1cm} (2)

It can be seen from the figure that the Nusselt number of the composite phase change material after adding graphite particles will increase compared to the basic phase change material at the same Reynolds number, and as the share of graphite particles gradually increases, the Nusselt number becomes relatively higher. This article uses formulas (1) and (2) to calculate the Nusselt number when the composite phase change thermal storage capsule melts under the corresponding Reynolds number.

Since the addition of graphite particles changes the overall structure of the composite phase change material, the overall characteristics of the capsule are more conducive to heat transfer, the melting of the material within a certain period of time is accelerated, and the temperature change is more obvious. Moreover, during the melting process, the temperature of the basic phase change material gradually increases, and the viscous resistance will also be reduced to a certain extent, which makes the melting process faster. Moreover, the dynamic irregular movement of graphite particles becomes more violent as the melting progresses, which further improves the overall thermal conductivity, reduces viscous resistance, strengthens convective heat transfer, and makes the time to reach the melting temperature shorter and shorter.
Fig. 4 Velocity vector diagrams of composite phase change materials with different proportions of 0, 0.85%, 1.25%, 1.75% at different times

Fig. 5 The relationship between Nu and Re under different composite phase change materials

5. Conclusion
The addition of graphite nanoparticles to the composite material is easier to melt. The movement of the nanoparticles further enhances the thermal disturbance and strengthens the natural convection. However, to a certain extent, because the viscosity increases, the strengthening is not obvious, and the movement speeds up and strengthens the convective heat transfer.

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