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NUMERICAL SIMULATION ON NATURAL CONVECTIVE HEAT TRANSFER PERFORMANCES OF MPCM SLURRY

Peng XIA, Guoying XU*, Lanxiong OUYANG, Qi CHEN, Ying YANG
Organization School of Energy and Environment, Southeast University, Nanjing 210096, China
*Corresponding Author. E-mail address: xugy@seu.edu.cn

ABSTRACT

Microencapsulated phase change material (mPCM) slurry has the advantages of excellent flow and heat transfer performance as traditional single-phase fluids and high heat storage density as phase change materials (PCM). In this paper, a three-dimensional numerical model of an immersed heat storage tank containing a vertical helical coiled tube was established. Combined with the physical properties of the prepared mPCM slurry, the coupling relationship between temperature and velocity field and the mPCM slurry's natural convective heat transfer process were simulated. The influence of particle concentrations on its heat transfer and storage performances was discussed. Results show that the heat transfer process of mPCM slurry can be divided into three stages: heat conduction dominated stage—convection development stage—convection attenuation stage. Although the increase in particle concentrations reduces the heat transfer coefficient, the heat storage capacity of mPCM slurry with 30% particle concentrations increases by 38.6% compared with base fluid (water).

Keywords: mPCM slurry, helical coiled tube, heat transfer coefficient, heat storage capacity

NONMENCLATURE

Abbreviations	
PCM	Phase change material
mPCM	Microencapsulated phase change material
Symbols	
t	Temperature (℃)
ω	Mass fraction (-)
P	Pitch (m)
D	Coil diameter (m)
α	Heat transfer coefficient ($W/m^2.K$)
Q	Heat storage capacity (MJ)
$\dot{Q}$	Heat flux (W)
A	Area of helical coiled tube's wall (m^2)
Subscripts	
wall	Helical coiled tube's wall
f	mPCM slurry

1. INTRODUCTION

Using phase change materials (PCM) to storage energy has the advantages of high energy storage density, small temperature variations and good safety. It is widely used in the fields of waste heat recovery, solar heat utilization and energy-efficiency buildings. At present, the researches on strengthening the efficiency of heat storage device mainly carried out from two aspects: one is to optimize the geometric structure of the heat exchangers: such as changing the arrangement or the shape of it, using micro-heat pipes and adding fins [1]. Compared with straight tubes, helical coiled heat exchangers have a higher surface area/volume ratio, that is, they only need to occupy a smaller volume in the tank to achieve higher heat flow output. Another is to improve the performance of PCM such as: compositing PCM and nanoparticles, adsorbing PCM with porous materials and microencapsulating PCM [2]. Among them, mPCM refers to microencapsulate the core PCM with organic or inorganic polymer walls to form a capsule with shell-core structure, and their particle size is generally about 0.1~1000 μm. Due to the protection of the shell, the leakage and phase separation problems can be avoided. Further, the so called mPCM slurry is by mixing mPCM particles and traditional single-phase fluids to form a stable slurry, which has the advantages of well fluidity, high thermal conductivity and heat storage density, and it has completely different characteristics from conventional single-phase fluid.

In this paper, a commonly used helical coiled tube immersed in a heat storage tank is adopted for solar heat pump heating systems. The natural convective heat transfer characteristics of mPCM slurry was analyzed, and the influence of particle concentrations on its heat transfer and storage performance was explored.

2. NUMERICAL MODEL

2.1 Physical and mathematical model

The physical model of the heat storage tank established in this paper is shown in Figure.1, where the negative direction of z-axis is the actual direction of gravity. The tank's diameter D_0 is 0.3m, and its height H_0 is 1.5m. The helical coiled tube's pitch P is 0.15m, and the coil diameter D is 0.2m. The tank is filled with different mass fractions of mPCM particles outside the tube. During the heat storage process, high temperature water flows through the tube to transfer heat to the outer mPCM slurry. All the necessary mathematical governing equations can be found in the work of Inaba [3].

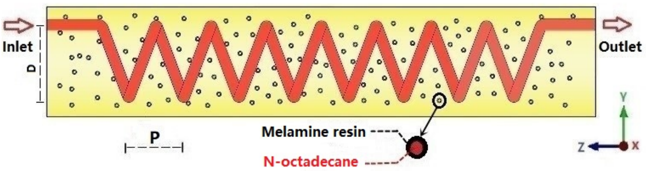

Fig.1 Physical model of the heat storage tank containing a helical coiled tube heat exchanger

2.2 Physical properties of mPCM slurry

In this article, the core material of our self-prepared mPCM is n-octadecane, its melting point is 25.56℃~ 30.12℃, and the wall material is melamine resin. Figure.2 shows the macro morphology and TEM image of the mPCM slurry with a mass fraction of 30%. It can be seen that the prepared mPCM slurry has well fluidity and is easy to pour; and the mPCM particles are nearly round, its diameter is about 300~400nm.

According to our previous experimental work [4], the density, viscosity and thermal conductivity of mPCM slurry were measured, and then fitted into the calculation formula. The specific heat capacity of slurry with different particle concentrations is listed as Fig.3.

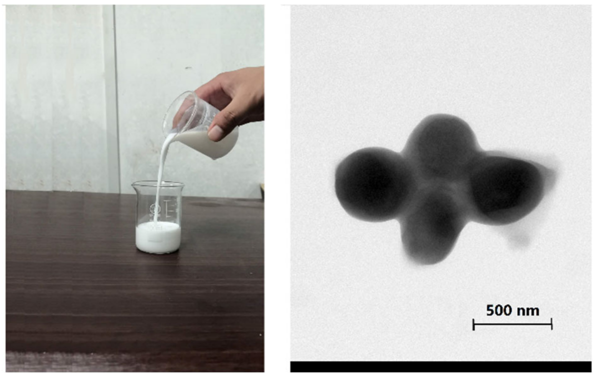

Fig.2 Macro morphology and TEM image of mPCM slurry

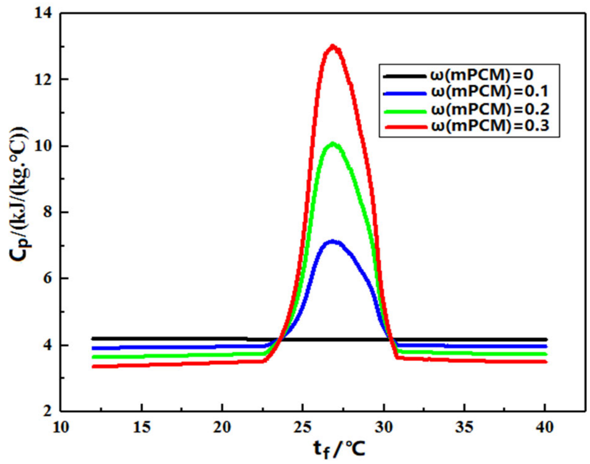

Fig.3 Specific heat capacity of different mass fractions

3. RESULTS AND DISCUSSION

3.1 Natural convective heat transfer characteristics

In this article, the initial temperature of the mPCM slurry in the tank is set to be 20°C, the inlet water's temperature is constantly 40°C, and the inlet flow rate is 1.2m/s. The average heat transfer coefficient α between the slurry and the helical coiled tube's wall is defined as follows:

$$\alpha = \frac{\dot{Q}}{A(t_{wall} - t_f)} \tag{1}$$

Fig.4 and Fig.5 are respectively the transient heat transfer coefficient curve and the temperature and velocity contour. From Fig.4, it can be concluded that during the entire heat storage process, the average natural convective heat transfer coefficient can reach 616.3 W/(m2.K)), which is significantly higher than that of bulk PCM that requires a considerable part of heat transferred by heat conduction. According to the heat transfer mechanism, the natural convective heat transfer process of mPCM slurry can be divided into three stages:

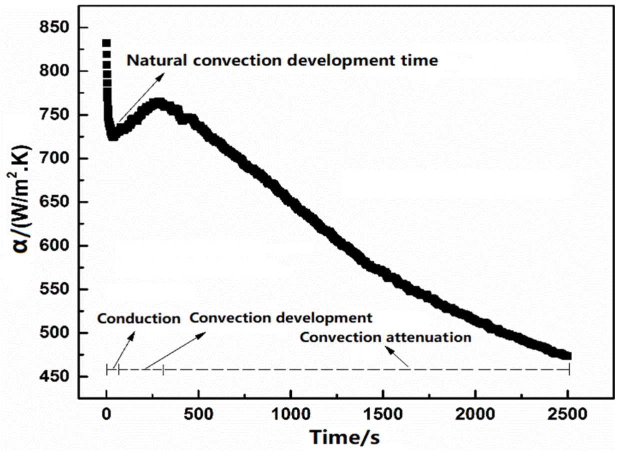

Fig.4 Transient heat transfer coefficient between helical coiled tube's wall and mPCM slurry

conduction dominated stage--convection development stage--convection attenuation stage.

In the initial stage of the heat storage process (t≤30s), due to the large temperature difference existed between the tube's wall and the mPCM slurry, the heat flux is high, so the heat transfer coefficient is high. As the fluid's temperature increases, the heat flux reduces, thus the heat transfer coefficient decreases. However, the temperature difference between the fluid near the wall and the surrounding fluid is still low, resulting in a relatively low velocity of the slurry. The heat transfer at this stage is dominated by heat conduction.

After that, as the temperature of the slurry near the wall further increases, the upward velocity caused by the buoyancy force increases, and the natural convection's effect is enhanced. Therefore, heat transfer coefficient gradually increases and it reaches a local peak value at t=320s. During this period, the natural convective heat transfer is at the development stage.

In the attenuation stage (t>320s), the temperature difference between the tube's wall and the mPCM slurry gradually decreases, and the unevenness of the temperature field in the heat storage tank gradually decreases, making the slurry's velocity gradually decay, and results in a monotonous decrease in the heat transfer coefficient.

3.2 The effect of particle concentration

3.2.1 Effect on heat transfer performance

Figure.6 shows the heat transfer coefficient curve of different particle concentrations over time. It can be seen that: (1) As the concentration increases, the heat transfer coefficient gradually decreases; (2) As the concentration increases, the development time of natural convection is continuously delayed.

First, the increase in concentration leads to a decrease in thermal conductivity and an increase in viscosity, which slows heat transfer and increases viscous resistance. It plays a negative role in the heat transfer coefficient and development of natural convection; Second, the increase in concentration increases the apparent specific heat capacity in the phase change interval, which is equivalent to acting as a heat sink [5], and it has a positive effect on the heat transfer coefficient and the development of natural convection.

It can be seen from Figure 6 that during the entire heat storage process, the heat transfer coefficient of higher concentration is less than that of the lower concentration, that is, the negative effects of the viscosity and thermal conductivity on the heat transfer performance exceeds the positive effect of specific heat capacity.

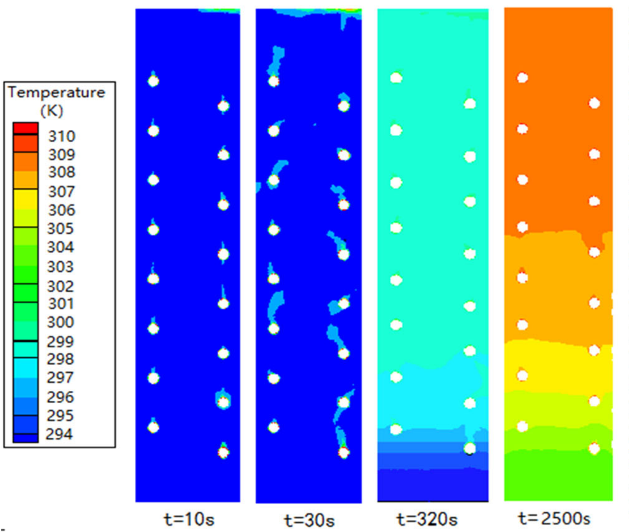

Fig.5(a) Temperature field

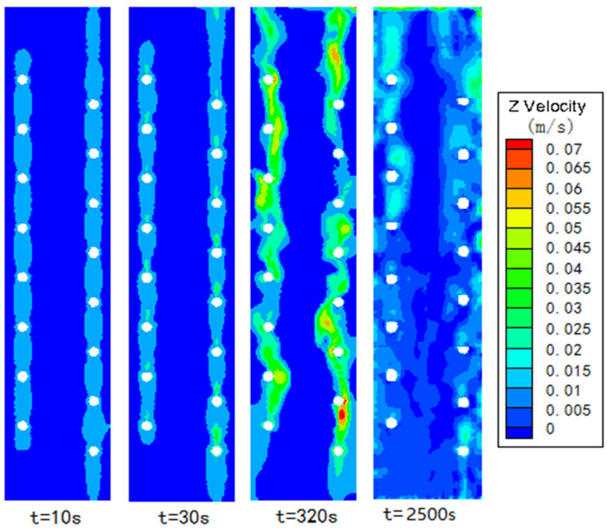

Fig.5(b) Velocity field

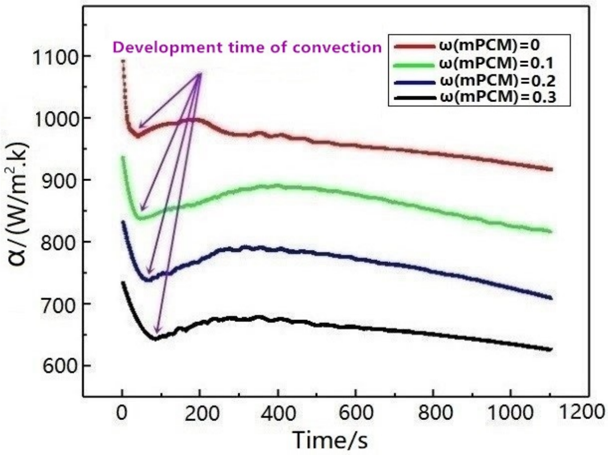

Fig.6 Transient heat transfer coefficient of different fractions

3.2.2 Effect on heat storage performance

Figure.7 shows the variation curves of different concentrations' heat storage capacity over the slurry's volume average temperature. It can be seen that before reaching the initial phase change temperature(25.56℃), the base liquid's heat storage capacity is always greater than other concentrations, and it decreases with the increase of mass concentration, which is due to the fact that in non-phase stage, the apparent specific heat capacity of the slurry decreases as the concentration increases.

For each concentration, after reaching the initial phase change temperature, the heat storage capacity increases sharply as the temperature increases, and the growing rate reaches peak value near the peak phase change temperature (27.52℃). Combined with Fig.3, we can find that this is due to the apparent specific heat capacity reaches a maximum value.

After that, the growing rate gradually slows down. When the temperature is higher than the terminal phase change temperature (30.12℃), the growing rate of high concentration is less than the lower concentration. However, due to the larger latent heat absorption of the high concentration slurry in previous phase change interval, the heat storage capacity is still significantly higher than the lower one. Compared with the base fluid (water), after adding 30% mPCM particle concentration, the heat storage capacity of the slurry increased from 7.50MJ to 10.18MJ, nearly increases by 38.6%.

3.3 Conclusions

In this paper, the natural convective heat transfer and storage performance of mPCM slurry filled between the heat storage tank and the helical coiled tube was studied. Results show that the heat transfer coefficient of mPCM slurry is significantly greater than that of bulk PCM. Although the increase in particle concentrations reduces the natural convective heat transfer performance, the heat storage capacity of mPCM slurry with 30% particle concentrations increases by 38.6% compared with base fluid.

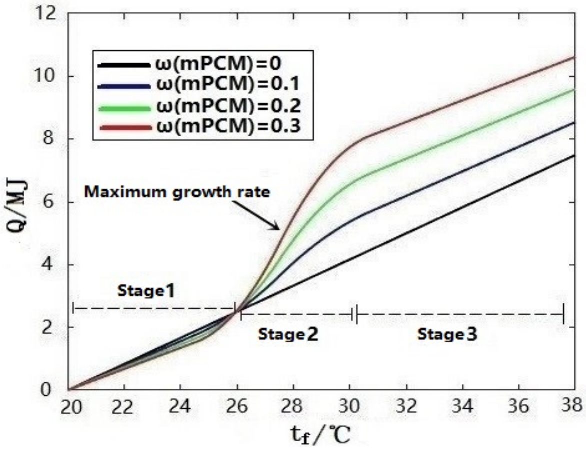

Fig.7 Heat storage capacity of different mass fractions

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