Numerical simulation of convective heat transfer of microencapsulated phase change material slurries in a circular tube

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Abstract. For the Microencapsulated Phase Change Materials slurry (MPCMs) having a large latent heat during the phase change period and having a higher heat convection coefficient than the single-phase fluid, it has become a new thermal fluid of widespread investigation. In this paper, the model of equivalent specific heat is presented to numerically simulate the laminar convective heat transfer performances of MPCMs in a tube under the condition of constant heat flux. The heat transfer of MPCMs in a tube is investigated under various concentrations of MPCMs and heat flux and the correlation of the convective heat transfer with MPCMs in a tube is obtained.

1. Introduction

The Microencapsulated Phase Change Materials slurry (MPCMs) is a kind of slurry mixed with MPCMs in a certain ratio. Phase Change Materials have large latent heat during the phase change period which can increase the heat transfer coefficient of the slurry. For its absorbing or releasing a lot of heat during the phase change period, it can reduce the degree of temperature change [1-4]. MPCMs has great promising applications in machinery, building [5], heat-scavenging, aviation, spaceflight, solar energy utilization, air conditioner [6], apparel and textiles [7-9].

In previous studies, most of them have studied the influence of various parameters on convective heat transfer characteristics of MPCMs in a tube by experiment and numerical simulation methods. There is a shortage of theoretical analysis of heat convection with MPCMs and the correlation of the convective heat transfer with MPCMs. In this paper, based on the reproduction experiment of convective heat transfer of MPCMs in a tube with numerical simulation and the fitting of the numerical simulation result of heat convection with MPCMs, the correlation of the convective heat transfer including Reynolds Number, Prandtl Number and Stefan Number is obtained, and its universality is certified.

2. Simulation model

2.1. Introduction of model

Figure 1 is a numerical simulation schematic drawing of heat convection under the condition of constant heat flux with MPCMs in a tube. It is a tube of 1.46m length, 4mm insider diameter. In the tube, all 14 temperature metrical points are set at the axial position of different positions along the pipe length direction.
2.2. Boundary conditions
The entrance of MPCMs is velocity-inlet, its velocity magnitude is 0.39 m/s and its temperature is 10.2 °C. The exit is an outflow. The tube wall is of constant heat flux, with heat flux density of 10103 W/m², 11546 W/m², 12990 W/m², 14433 W/m², 15876 W/m², 17320 W/m² and 18763 W/m² respectively. All MPCMs are composed of 5wt%, 10wt%, 15.8wt% 1-bromohexadecane micro-particles and their physical properties are listed in Table 1.

### Table 1: Physical properties of MPCM suspension

| Density (kg/m³) | Specific Heat (J/kg·K) | Thermal Conductivity (W/m·K) | Viscosity (kg/m·s) | Latent Heat (kJ/Kg) |
|----------------|------------------------|-----------------------------|--------------------|--------------------|
| water          | 998.2                  | 4182                        | 0.6                | 0                  |
| 5wt%           | 1000                   | 4054                        | 0.576              | 0.001003           |
| 10wt%          | 1002                   | 3926                        | 0.553              | 0.00202            |
| 15.8wt%        | 1005                   | 3776                        | 0.527              | 0.00375            |

2.3. Model of equivalent specific heat
When the temperature of the MPCM is in the phase change region, the specific heat will increase significantly. In Ref[10], four equivalent specific heat models of the MPCMs are given, which are rectangle, sine curve, left triangle and right triangle. Four models are shown in Figure 2.

![Figure 2. Four models of equivalent specific heat](image)

To simplify the numerical model, the rectangular equivalent specific heat model is adopted in this paper. The MPCMs which is composed of 1-bromohexadecane as the core material is taken as the research object. The phase transition point and latent heat of the MPCM were measured by Differential Scanning Calorimeter. It begins to melt at 14.3 °C and ends at 18 °C[11]. And the qualitative temperature is 15 °C which is calculated by the average temperature of slurry in the tube.

The equivalent specific heat is calculated as follows:

\[
C_{p,b} = \begin{cases} 
    C_{p,b0} & T \leq T_1 \\
    C_{p,b0} + \frac{h_f}{T_2 - T_1} & T_1 \leq T \leq T_2 \\
    C_{p,b0} & T \geq T_2 
\end{cases}
\]

Where \( C_{p,b} \) is the specific heat of MPCMs(J/Kg · °C), \( C_{p,b0} \) is the specific heat of single-phase fluid(J/Kg · °C), \( h_f \) is the latent heat of the slurry(kJ/Kg), \( T_1 \) is the starting melting temperature(°C) and \( T_2 \) is the ending melting temperature(°C).
3. Results and discussion

3.1. Validation of numerical simulation results
To verify the accuracy of the numerical simulation results of the equivalent specific heat model, the numerical simulation results of the 15.8% MPCMs whose velocity magnitude is 0.39 m/s and the temperature is 10.2 °C are compared with the experimental results of Chen[15] under the same conditions. The results show that the slurry temperature curves of the numerical simulation results and the experimental results are in good agreement, and their wall temperature trends are the same, and the error is small. Therefore, the numerical simulation results are close to the real situation.

Figure 3. Validation of numerical simulation results

Figure 4 shows the temperature profile of the numerical simulation results, where the white point is the temperature measuring point; the outer position is the liquid region and the temperature is lower than the starting melting temperature; the inner position is the solid region and the temperature is higher than the ending melting temperature; the middle position is phase change region and the temperature is between the starting melting temperature and the ending melting temperature. From Fig.4 the thickness of the liquid region is getting thicker and the thickness of the solid region is getting narrow towards the slurry flow direction.

Figure 4. Temperature profile

3.2. Numerical simulation result
At a given velocity magnitude, temperature and concentrations, the relationship between Nusselt Number and X+ under various heat flux density is shown in Figure 5. From the figure, the Nusselt Number decreases along the slurry flow direction and the Nusselt Number decreases with the increase of the heat flux density. The heat flux is not the main influence factors.

Figure 5. Numerical simulation result of heat convection with MPCMs under various heat flux density

Figure 6. Numerical simulation result of heat convection with various concentrations of MPCMs
At a given velocity magnitude, temperature and heat flux density, the relationship between Nusselt Number and X+ with various concentrations of MPCMs is shown in Figure 6. From the figure, the
Nusselt Number decreases along the slurry flow direction and the Nusselt Number increases with the increase of the concentrations of MPCMs. The concentration of MPCMs is not the main influence factor.

The dimensionless axial length can be denoted as follows:

\[ x^+ = \frac{x}{r} \frac{Pr}{Re} \]  

(2)

Where \( x \) is the length of the axis(m) and \( r \) is the inner radius of the tube(m).

3.3. Correlation of the numerical simulation result

To analyze the situation of heat convection with MPCMs, Stefan Number can be obtained as follows:

\[ Ste = \frac{q_w}{m h_f} - 1 = \frac{\pi dx q_w^*}{du \rho h_f} - 1 = \frac{4q_w^* x}{du \rho h_f} - 1 \]  

(3)

Where \( q_w \) is the heat flux(w), \( q_w^* \) is the heat flux density(w/m²), \( d \) is the inner diameter of the tube(m), \( m \) is the Mass flow rate(Kg/s), \( u \) The average velocity of the slurry(m/s) and \( \rho \) is the density of the slurry(Kg/m³).

To obtain the correlation of convective heat transfer with MPCMs in a tube, the correlation of the local Nusselt Number of the single-phase laminar developing flow in thermally developing region under a constant wall heat flux is used in this paper.

\[ Nu_{0, x} = 5.364 \left[ 1 + \left( \frac{110x^+}{\pi} \right)^{10/9} \right]^{3/10} - 1.0 \]  

In this paper, Stefan Number is introduced into the correlation. By fitting and simplifying, the correlation of the local Nusselt Number of the MPCMs laminar developing flow under a constant wall heat flux can be obtained as follows:

\[ Nu = 5.695 \left[ 1 + \left( \frac{110x}{\pi \sqrt{Re \cdot Pr}} \right)^{10/9} \right]^{3/10} (Ste + 1)^{-0.051} - 1.0 \]  

(5)

3.4. Universality of the correlation

To certify the universality of the correlation, the geometric and physical conditions are changed to be numerically simulated in this paper.

According to formula 3, Stefan Number is determined by the type of MPCMs, heat flux density, axis length, the inner diameter of the tube and the velocity of the slurry in this paper. The type of MPCMs, heat flux density and axis length have been changed to obtain the correlation of the local Nusselt Number and then change the inner diameter of the tube and the velocity of the slurry to numerical simulate again.

Keep the length of the tube 1.46m, the concentration of MPCMs 15.8wt% and the inner diameter of the tube 4mm and change the velocity of the slurry to 0.52m/s to numerical simulate. Keep the length of the tube 1.46m, the concentration of MPCMs 15.8wt% and the velocity of the slurry 0.39m/s and change the inner diameter of the tube to 5mm to numerical simulate. Compare the numerical simulation result with the calculated result. As shown in Figure 7, the numerical simulation result and the calculated result are in good agreement. Therefore, the universality of the correlation of convective heat transfer with MPCMs in a tube is certified.
4. Conclusions
In this paper, the model of equivalent specific heat is used to numerical simulate the laminar convective heat transfer performances of MPCMs in a tube under the condition of constant heat flux. The heat transfer of MPCMs in a tube is investigated under various concentrations of MPCMs and heat flux and the correlation of the convective heat transfer with MPCMs in a tube is obtained. And change the inner diameter of the tube and the velocity of the slurry to certify the universality of the correlation of convective heat transfer with MPCMs in a tube.

- The effect of concentration of MPCMs and heat flux density on the laminar heat transfer with MPCMs under a constant wall heat flux is not significant.
- The correlation of the convective heat transfer is presented which includes Reynolds Number, Prandtl Number and Stefan Number.
- The correlation of the local Nusselt Number has a good universal.

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