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Numerical simulation of heat transfer of latent functionally thermal fluid in tubes with coaxially inserted cylindrical bars in laminar

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The heat transfer of latent functionally thermal fluid in three kinds of tubes with coaxially inserted cylindrical bars is numerically researched using equivalent specific heat model, and the flow fields are analyzed with field synergy field. It is found that in the tubes with coaxially inserted cylindrical bars, the heat transfer effects of functionally thermal fluid become more and more pronounced with the *Ste* decreasing. This is similar to be case of functionally thermal fluid flowing in smooth straight tubes. Compared with the results receiving from smooth straight tubes, the heat transfer of functional thermal fluid in tubes with coaxially inserted cylindrical bars has been significantly enhanced. And this effect becomes more apparent as the diameter of coaxially inserted cylindrical bars increases meanwhile, however, energy consuming of the tubes shows the same trend.

latent functionally thermal fluid, field synergy, equivalent heat specific, microencapsulated phase change material

1 Introduction

Microencapsulated phase change material (MEPCM) is a kind of particles with sizes ranging from 1 to 100 μm. The core of particles is consisted of phase change material, whereas the shell is made of polymers (Melamine resin, Urea-formaldehyde resin, Gelatin, etc.) A kind of suspension can be achieved by dispersing the particles in some based liquid. Using this novel suspension could lead to a lot of potential benefits, for instance, huge specific heat capacity associated with phase change process can be obtained with little temperature changing; the volume and flow structure of the coolant remain unchangeable during the phase change process. Therefore, this new coolant has attracted more and more attention since it was first proposed two decades ago. Choi et al.[1], Goel et

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al.[2], Yamagishi et al.[3] and Wang et al.[4] experimentally researched the flow and heat transfer characteristics of MEPCM suspension flowing in metal circular tubes; Choi et al.[5] and Rao[6] experimentally investigated the heat transfer of MEPCM suspension flowing in rectangular channels. In the aspect of numerical simulation, Charunyakorn et al.[7], Zhang et al.[8,9] studied the heat transfer and flow of MEPCM suspension flowing in circular tubes by using inner heat source model, while Hu et al.[10], Daniel et al. [11] and Edwin et al.[12] carried out the simulation about MEPCM suspension with an equivalent specific heat model. All the foregoing researchers attained a similar conclusion: Compared with pure water, using MEPCM suspension could significantly enhance heat transfer.

To the best of the author' knowledge, the existing research mainly were confined to the flow of MEPCM suspension in some normal tubes, including circular or rectangular ones, which could make the researchers grasp some heat transfer nature of MEPCM suspension conveniently. In the practical application, however, there is a wide range of special tubes which are manufactured using convective heat transfer enhancement technology in the heat transfer equipment beside normal tubes. Hence, it is meaningful to carry out the research about the heat transfer characteristics of MEPCM suspension flowing in special tubes. This formed the primary motivation of this work.

Fu et al.[13] reported that the convective heat transfer could be distinctly enhanced by using circular tubes with coaxially inserted small tubes. Following that work, Yu et al.[14] experimentally studied tubes with coaxially inserted cylindrical bars and found this kind of tube could further enhance the convective heat transfer. All the forenamed conclusions were attained associated with pure water. In this paper, the flow and heat transfer of MEPCM suspension of 10 vol. % flowing in circular tubes with coaxially inserted cylindrical bars, which is a combination of two different convective heat transfer enhancement technologies, are studied using an equivalent specific heat model. The field synergy theory proposed by Guo et al.[15] is used to analyze the flow field and the convective heat transfer enhancement effects accompanying with MEPCM suspension flowing in this special tube are also summed up.

2 Brief introduction of field synergy theory

In 1998 Guo et al.[15] and his co-workers proposed a novel concept of enhancing convective heat transfer, and obtained the following equation:

$$Nu_x = Re_x Pr \int_0^1 \left(\overline{U} \cdot \nabla \overline{T}\right) \mathrm{d}\overline{y}, \tag{1}$$

It is evident that there are three ways to increase convective heat transfer: (a) increasing Reynolds number; (b) increasing Prandtl numbers; (c) increasing the value of integral item. The dot product item in the integral $\overline{U} \cdot \nabla T$ can be rewritten as

$$\overline{U} \cdot \nabla \overline{T} = \left|\overline{U}\right|\left|\nabla \overline{T}\right| \cos \beta, \tag{2}$$

where β is the intersection angle between the velocity vector and temperature gradient. Hence, the value of integral depends on no only the values of $\overline{U}$ and $\nabla \overline{T}$ but also the intersection angle between the two vectors. Most convective heat transfer problems encountered in engineering are of elliptic type, and hence, Tao et al.[16] extended the field synergy principle to elliptic cases, and then Zeng et al.[17] extended it to turbulence cases.

3 Numerical model and verification

3.1 Description of computing region

The sketch of a circular tube with coaxially inserted cylindrical bars is shown in Figure 1(a). In the front section designated as *Lt*, a series of cylindrical bars are inserted at equal intervals. The rear section designated as *Ls* is smooth, so that outflow can be used as boundary condition at the outlet. In this paper, the attention is only focused on the front section, *Lt*. A unit of the tube is also shown in Figure 1(b), and the geometric parameters can be found in Table1.

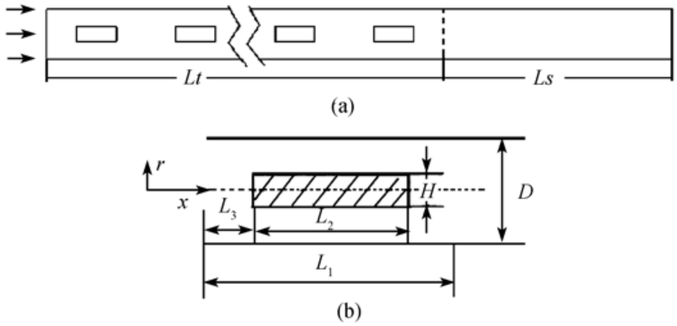

Figure 1 Sketch of circular tube with coaxially inserted cylindrical bars.

Table 1 Geometric parameters of tubes with coaxially inserted cylindrical bars (mm)

	L_1	L_2	L_3	H	D	Lt	Ls
Tube 1	50	20	15	1	10	2000	500
Tube 2	50	20	15	1	10	2000	500
Tube 3	50	20	15	1	10	2000	500

3.2 Model formulation

Assumptions invoked by this model are as follows.

1) The flow of suspension remains laminar.
2) Density change associated with solid-liquid change in the particles is neglected.
3) The density difference between particles and based liquid is neglected.
4) The particles are dispersed in the based liquid evenly.
5) Viscous dissipation and axial thermal conduction are neglected.
6) There are no internal and external heat sources.
7) All the physical properties of suspension are constant except $c_{p,b}$.

Then, the control equations of suspension under two dimensional polar coordinates are as follows.

Equation of continuity:

$$\frac{\partial u}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}\left(rv_r\right)=0. \tag{3}$$

Equations of momentum:

$$\rho_b u\frac{\partial u}{\partial x}+\rho_b v_r\frac{\partial u}{\partial r}=-\frac{\partial P}{\partial x}+\mu_b\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right)+\frac{\partial^2 u}{\partial x^2}\right], \tag{4a}$$

$$\rho_b u\frac{\partial v_r}{\partial x}+\rho_b v_r\frac{\partial v_r}{\partial r}=-\frac{\partial P}{\partial r}+\mu_b\left\{\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}(rv_r)\right]+\frac{\partial^2 v_r}{\partial x^2}\right\}, \tag{4b}$$

where ρ_b is the density of suspension, μ_b is dynamic viscosity of suspension, and r_d is the radius of tube.

Boundary conditions for equations of momentum: $u\,|_{x=0}=u_m$, $u\,|_{r=r_d}=0$, $\left.\frac{\partial u}{\partial y}\right|_{r=0}=0$, $v_r\,|_{x=0}=0$, the surfaces of coaxially inserted cylindrical bars are defined as non-slip wall; outlet is defined as outflow.

Equation of energy:

$$\rho_b c_{p,b}\left(u\frac{\partial T}{\partial x}+v_r\frac{\partial T}{\partial r}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(rk_e\frac{\partial T}{\partial R}\right). \tag{5}$$

Boundary conditions for equation of energy: $T\,|_{x=0}=T_i$, $\left.\frac{\partial T}{\partial r}\right|_{r=0}=0$, $\left.\frac{\partial T}{\partial r}\right|_{r=r_d}=\frac{q_w}{k_{e,w}}$. No heat flux imposes on the wall of coaxial inserted cylindrical bars; the outlet is defined as outflow.

In eq. (5), $c_{p,b}$ is the specific heat capacity of suspension, k_e is the effective thermal conductivity of suspension which follows the definition in [7]:

$$\begin{cases} k_e=f\cdot k_b, \\ k_b=k_f\cdot\dfrac{2+k_p/k_f+2c\left(k_p/k_f-1\right)}{2+k_p/k_f-c\left(k_p/k_f-1\right)}, \\ f=1+BcPe_p{}^m, \\ B=3.0,\ \ m=1.5,\ \ Pe_p<0.67, \\ B=1.8,\ \ m=0.18,\ \ 0.67\leqslant Pe_p\leqslant 250, \\ B=3.0,\ \ m=\dfrac{1}{11},\ \ Pe_p>250, \end{cases} \tag{6}$$

where k_b is the thermal conductivity of quiescent suspension, k_p is thermal conductivity of particles, k_f is the thermal conductivity of based liquid. $Pe_p=\frac{er_p^2}{a_f}$ is the Peclet number of particles, e is the velocity gradient of suspension, r_p is the particle radius, a_f is the thermal diffusivity of based liquid, ρ_b is the density of suspension, which is described as[7]:

$$\rho_b=\rho_p\cdot c+\rho_f\cdot(1-c),$$

where ρ_p is the density of particles, and ρ_f is the density of based liquid.

μ_b is the dynamic viscosity of suspension[7]:

$$\frac{\mu_b}{\mu_f}=(1-c-1.16c^2)^{-2.5}. \tag{7}$$

$c_{p,p}$ is the specific heat of particles, which is a function of temperature within $T_1\leqslant T\leqslant T_2$, where T_1 and T_2 are the beginning and ending temperatures of phase change process, respectively. Though some researchers observed that the $c_{p,p}-T$ curve has several different shapes, the shape of the specific heat-temperature curve has a very small effect on the heat transfer rates from a phase change material suspension. As a result, it is possible to assume that the specific heat capacity of the particles remains constant during the phase change process. The following equation can then be used to evaluate the specific heat of the particles during the melting process:

$$c_{p,p} = \frac{L}{T_2 - T_1}.$$

$c_{p,b}$ is the bulk specific heat of suspension, defined as[7]

$$c_{p,b0} = c \cdot c_{p,ps} + (1-c) \cdot c_{p,f}, \qquad T < T_1 \text{ or } T > T_2,$$

$$c_{p,b} = c \cdot c_{p,pm} + (1-c) \cdot c_{p,f}, \qquad T_1 \leqslant T \leqslant T_2,$$

where $c_{p,ps}$ is the specific heat of particles when the melting process is over, and $c_{p,pm}$ is the specific heat of particles during the melting process.

Some dimensionless numbers are defined as

$$\theta_{wx} = \frac{T_w - T_i}{q_w r_d / k_b}, \quad \bar{x} = \frac{x}{Re_b Pr_b r_d}, \quad Ste = \frac{c_{p,b} \cdot q_w r_d / k_b}{cL \rho_p / \rho_b}.$$

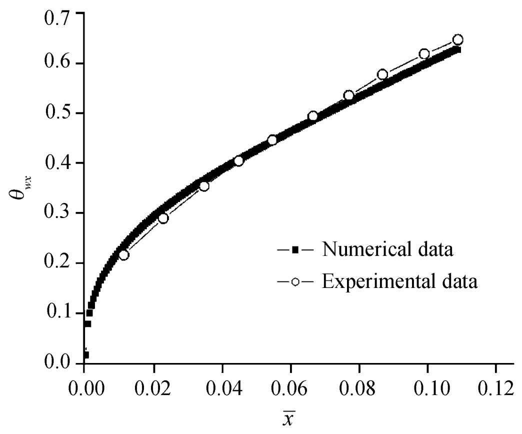

Figure 2 Comparison of numerical results with experimental data[2]. (Ste=1.0, $\frac{T_i - T_1}{q_w r_d / k_b} = -0.07$, $\frac{T_2 - T_1}{q_w r_d / k_b} = 0.4$, c =0.1, r_d= 1.57 mm, r_p= 50 μm, Re_b= 200).

3.3 Model verification

Eqs. (3), (4) and (5) are discretized using the finite volume method. The pressure-velocity coupling has been treated using the SIMPLEC algorithm.

The model verification is necessary. Cases of pure water flowing in smooth tube are studied using this model, and the results agree with theoretical data very well. Due to lack of experimental data related to MEPCM suspension flowing in tubes with coaxially inserted cylindrical bars, in this paper, MEPCM suspension flowing in smooth tube is investigated and results are compared with experimental data[2], as shown in Figure 2. The difference between numerical prediction and experimental data is small, indicating the model provides an adequate prediction for circular smooth tubes.

4 Results and analysis

4.1 Flow field of pure water

In this paper, the flowing of pure water in a smooth tube, Tube 1, Tube 2 and Tube 3 (which are shortened to ST, BT-1, BT-2, and BT-3, respectively at the rest of this paper) has been studied at first. The distribution of intersection angle between the velocity vector and the temperature gradient can be seen in Figure 3.

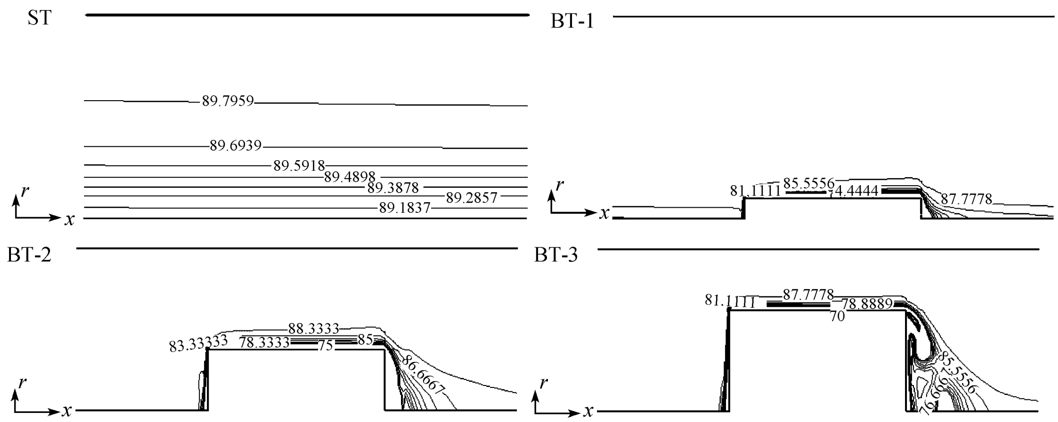

Figure 3 Distribution of intersection angles between the velocity vector and the temperature gradient. (Re = 200, q_w = 1900 W/m^2).

As shown in Figure 3, β in the entire flow field of ST is close to 90 degrees, indicating that velocity vector and temperature gradient are almost vertical. It can be seen from eqs. (1) and (2) that radial convective heat transfer effect is tiny when the flow has fully developed. The heat transfer from wall into interior of flow field mainly relies on heat conduction, making the heat transfer rate very low. As a result, the temperature nearby the wall has been very high, whereas the temperature nearby the tube axis is low, leading to a significant radial temperature gradient.

There are two effects for MEPCM suspension to enhance heat transfer: (a) rising thermal conductivity caused by micro-convective; (b) high effective specific heat capacity near the phase change temperature. When the ratio r_p/D is small[18], the effect of micro-convective is very little (refer to eq. (6)), making the effective specific heat the only factor to enhance heat transfer. The particles nearby the wall have opportunity to melt quickly and absorb latent heat, whereas those nearby the tube axis may flow out of outlet without melting completely where high radial temperature gradient happens. Hence, the high radial temperature gradient is an adverse factor for the application of MEPCM suspension.

As shown in Figure 3, the coaxially inserted cylindrical bars have changed the distribution of velocity and temperature in the flow field, making β significantly reduced and radial convective heat transfer enhanced. β is further reduced as the diameters of bars increases. All the foregoing effects lead to a pronounced reduction of radial temperature gradient. In this new flow field, the particles could melt more quickly and completely.

4.2 Wall temperature

The flow and heat transfer of suspension with 10 vol. % flowing in ST, BT-1, BT-2 and BT-3 have been investigated using the equivalent specific heat model. Based on the results in the literature *Ste* number is considered as the factor that affects the performance of MEPCM suspension the most. Hence, the dimensionless wall temperatures under different *Ste* numbers have been shown in Figure 4 first.

As shown in Figure 4, the wall temperatures of BT-1, BT-2 and BT-3 exhibit a jagged fashion, which is caused by the periodic changing cross-sectional area of tube. When the suspension flows through the gap between wall and coaxial inserted cylindrical bar, the velocity is heightened due to

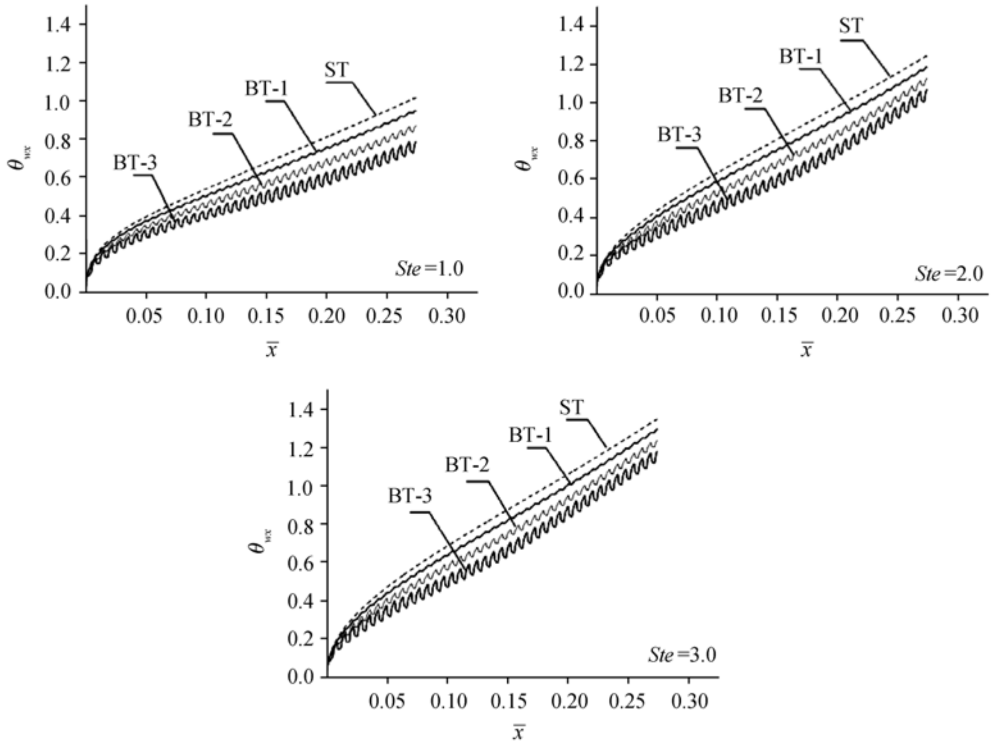

Figure 4 Wall temperatures along the length of tubes under different *Ste* numbers (Re = 200, c = 0.1).

the contracted area, making the heat transfer enhanced and local wall temperature dropped; in contrast, when the flow reaches section between two bars, the velocity goes down due to the increasing area, making the heat transfer descended and local wall temperature rising.

Similar to the cases related to smooth tubes, the wall temperatures of BT-1, BT-2 and BT-3 descend as the *Ste* number decreases, indicating better performance of heat transfer. Although the similar trend, the wall temperatures of BT-1, BT-2 and BT-3 are much lower than that of ST, and this difference is turning more apparent as the diameter of bars increases

As mentioned above, the velocity vector and temperature gradient are almost vertical when the flow fully develops in smooth tubes, leading to a relatively large radial temperature gradient. In the flow field with a large radial temperature gradient, the particles nearby the axis melt slowly, imposing a negative effect on the performance of MEPCM suspension. When the flow field is rearranged by coaxial inserted cylindrical bars, radial convective heat transfer is enhanced, causing heat transfer from wall into interior within shorter time. As a result, the particles inside the tube could melt more completely and quickly, absorbing more latent heat. The performance of MEPCM suspension hence has been enhanced. Moreover, this effect can be further heightened through increasing diameter of bars, because the intersection angle between velocity vectors and temperature gradient decrease as the diameter of bars increases (as shown in Figure 3).

It is manifest that the MEPCM can only enhance the heat transfer during the melting process. Hence it is highly necessary to investigate the percentage of particles undergoing melting at different cross-section along the length, because high percentage indicates better performance of heat transfer. As shown in Figure 5, the percentages of particles undergoing melting at cross-sections for

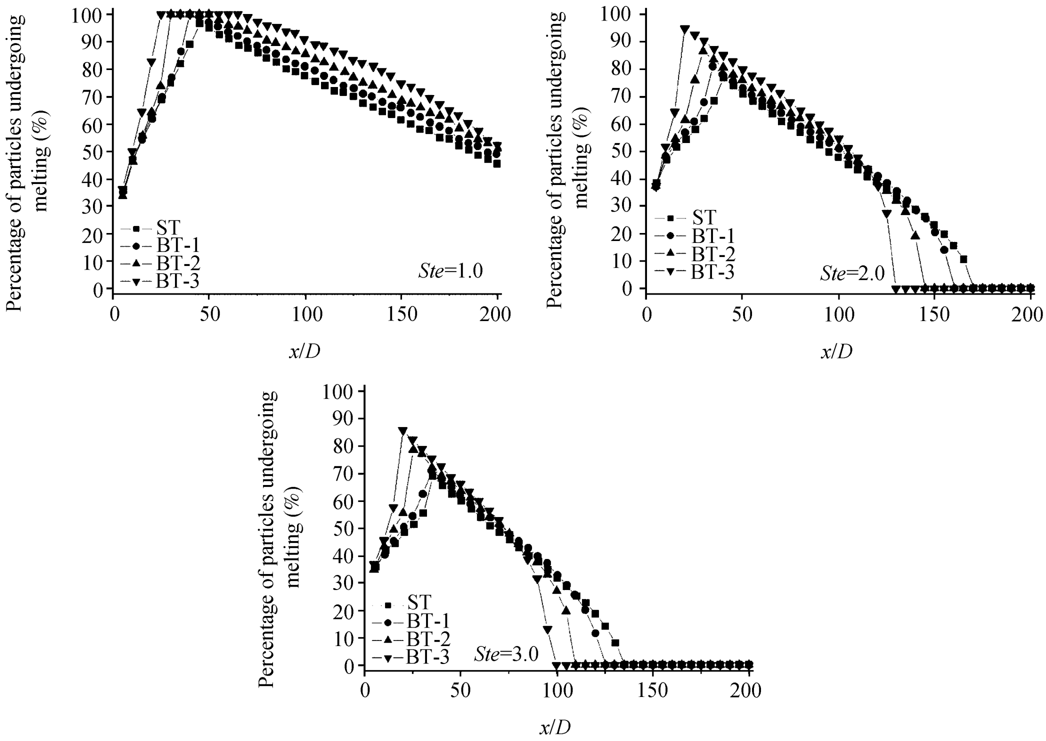

Figure 5 Percentages of particles undergoing melting (Re=200, c=0.1).

all tubes increase as the *Ste* number decreases, which explains the reason why MEPCM suspension reveals better heat transfer performance under small *Ste* numbers.

The percentage of particles undergoing melting for BT-3 is the largest, meanwhile, the phase change process ends the earliest. For instance, the particles have melted completely at the outlet when Ste = 2.0 and Ste = 3.0. Cases of BT-1 and BT-2 show the similar trend of BT-3, however, a relatively small percentage of particles undergoing melting. Compared with BT-1, BT-2 and BT-3, the percentage of particles undergoing melting is the smallest, and the phase change process ends the latest. Based on all the phenomena mentioned above, it is reasonable to conclude that there are at least three different effects to enhance the convective heat transfer when MEPCM suspension is flowing in tubes with coaxially inserted cylindrical bars.

1) The latent heat associated with phase change process could significantly increase the value of *Pr* in eq. (1).

2) The intersection angle between velocity vector and temperature gradient decreases due to the coaxially inserted cylindrical bars, causing the value of integral in eq. (4) to increase.

3) Heat could transfer from wall to interior of flow field easily, making the particles melt quickly and completely, absorbing huge amount of latent heat.

4.3 Heat transfer characteristics

In order to analyze the convective heat transfer conveniently, a dimensionless number is defined as follows

$$\eta = Nu^*_{x,\text{mepcm}} \Big/ Nu^*_{x,\text{water}} ,$$

where $Nu^*_{x,\text{mepcm}}$ and $Nu^*_{x,\text{water}}$ are the local Nusselt number of MEPCM suspension and pure water flowing in tubes, respectively. It should be noted that the conventional Nusselt number correlation cannot accurately describe convective heat transfer of MEPCM suspension whose apparent specific heat is strongly temperature dependent[9]. The modified definition of local Nusselt number proposed in [9] has been used in this paper: $Nu^*_x = \frac{q_w}{T_w - T_i} \cdot \frac{D}{k_b}$.

As shown in Figure 6, compared with smooth tube, tubes with coaxially inserted cylindrical bars could make the MEPCM suspension more effective in heat transfer, and this effect could be more pronounced as the diameter of bar increases.

In the practical application, energy consuming of the system is one of the main factors designers must emphasize. Hence the performance of MEPCM suspension in different tubes under the same energy consuming $(\dot{m}/\rho)\Delta p$[19] has been studied in this paper, where $\dot{m}$ is the mass flow rate of MEPCM suspension, and Δp is the pressure drop of the tube.

As shown in Figure 7, under the same consuming energy, the local Nusselt numbers of ST and BT-1 are almost the same, while that of BT-2 is lower, and BT-3 is the lowest, which is due to the increment of pressure drop caused by coaxially inserted cylindrical bars. When *Re*=200, the pressure drop of BT-1 is higher than that of ST by 118%, and that value is 300% for BT-2. The high pressure drop lowers the flowing velocity under the same consuming energy, making the local Nusselt number go down. From the aspect of heat transfer, the system could benefit from the bars with a large diameter. The diameter of bars, however, should be modest where the consuming energy also must be considered. How to enhance the heat transfer with little penalty due to increase in pressure drop is the work in the future.

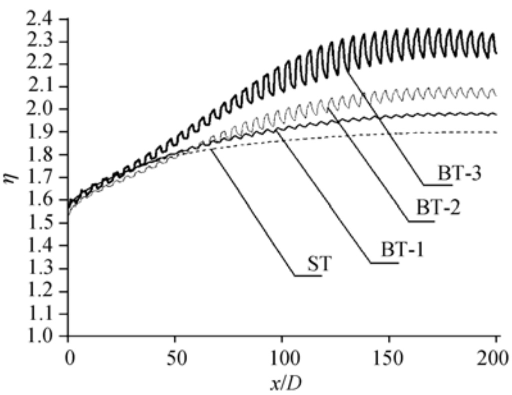

Figure 6 Convective heat transfer for different tubes under the same *Re* number (*Ste*=1.0, *c*=0.1, *Re*=200).

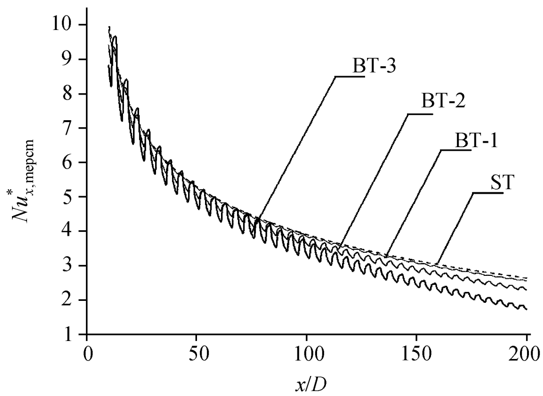

Figure 7 Convective heat transfer for different tubes under the same consuming energy (*Ste*=1.0, *c*=0.1).

5 Conclusions

In this paper, the flow and heat transfer characteristics of MEPCM suspension flowing in tubes with coaxially inserted cylindrical bars have been studied using the equivalent specific heat model. The following conclusions can be drawn from the results.

1) The enhancement of heat transfer for MEPCM suspension flowing in tubes with coaxially

inserted cylindrical bars increases with the *Ste* number decreasing.

2) The inserted cylindrical bars could significantly reduce the intersection angle between velocity vectors and temperature gradient, making the heat transfer from wall to interior easily. In this novel flow field, MEPCM could melt quickly and completely, absorbing huge amount of latent heat. This effect is more pronounced as the diameter of bars increases.

3) The pressure drop increases dramatically with the diameter of bars increasing. Hence the diameter of bars should be modest where consuming energy must be considered.

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