NUMERICAL SIMULATION OF PARAFFIN MELTING IN CIRCULAR TUBE USING LATTICE BOLTZMANN METHOD

by

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Paraffin melting is widely used in the fields of phase change materials energy storage, gathering and transportation pipe-line paraffin removal, etc. Analysis of the phase change mechanism and influencing factors of paraffin melting in the circular tube deeply has important guiding significance for improving the heat storage capacity by changing the structure of phase change material storage device and ensuring the safe transportation of crude-oil in the pipe-line. A double distribution lattice Boltzmann model based on enthalpy method is established to simulate the temperature field and the flow field of paraffin melting in a circular tube in this paper. The influence of different Rayleigh and Prandtl numbers on the paraffin melting process in a circular tube is analyzed. The results show that the natural-convection process is strengthened with the increase of the Rayleigh number, and the decrease of the average Nusselt number on the wall is smooth in the transition stage of wax melting due to the existence of fuzzy zone. The melting rate of paraffin can be accelerated or reduced by controlling the Prandtl number, so as to meet the relevant requirements of engineering.

Keywords: phase change, heat transfer, paraffin, melting, circular tube, lattice Boltzmann method

Introduction

Paraffin phase change process has wide and important applications in many fields, such as building energy saving, energy utilization, space exploration, pipe-line paraffin removal and other fields [1-5]. Because of the wide melting temperature range and high latent heat of paraffin, the research on paraffin melting at domestic and foreign mainly focuses on the field of phase change materials, including the preparation methods of PCM [6] and the improvement of solid-liquid phase-change heat transfer [7-10]. Grel [11] used the finite volume method to numerically study the melting heat transfer in the latent heat storage system of three different shape plate heat exchangers with RT-35 and n-octadecane as PCM. Zhang *et al.* [12] proposed an unsteady model of solidification heat transfer in a LHS unit with tree-shaped fins is developed and numerically analyzed using CFD software, in an effort to demonstrate the improvement of the energy discharging performance for a latent heat storage unit using fractal tree-shaped fins. Tan *et al.* [13] revealed the strong existence of the expected unstable flow structure at the bottom of the sphere and its influence by comparing the melting of paraffin in the spherical capsule with the simulated melting time.

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In addition, as an important component of crude-oil, the solubility of paraffin in crude-oil decreases with the decrease of crude-oil temperature. Therefore, paraffin deposition in the pipe-line is one of the inevitable serious problems in crude-oil production and transportation. Due to its simple operation and low cost, hot washing is the most commonly used method in the actual operation of an oilfield [14]. The process of paraffin removal by thermal washing is a complex process involving the phase change heat transfer during paraffin melting. At present, research on pipe-line paraffin removal is mostly focused on the improvement and optimization of paraffin removal technology, while in the field of paraffin removal, there is less research on the mechanism of paraffin melting process itself. Xu *et al.* [15] proposed a new generalized phase transition partition model to describe the waxing process of crude-oil. The FLUENT software was used to simulate the effects of different width phase transition temperature regions and porous media permeability on the phase transition heat transfer process of crude-oil. Ghosh *et al.* [16] used the enthalpy porosity model in fluent software to simulate the solidification of paraffin in spherical cavity and rectangular cavity according to different thermal boundary conditions. Jiang *et al.* [4] used enthalpy porosity and fluid volume method to simulate the melting of paraffin in crude-oil gathering and transportation pipe-line. Li *et al.* [17] established the mathematical model of phase change heat transfer and multi-phase flow coupling problem, and studied the effects of water temperature, spherical paraffin size and initial temperature on paraffin melting and flow characteristics under natural-convection conditions by using FLUENT software.

It can be seen that PCM energy storage and pipe-line paraffin removal are related to the melting of paraffin in the pipe. In the existing literature, the simulation research of paraffin melting is usually to establish 2-D or 3-D physical model on the macro scale, using the traditional CFD method based on continuous medium assumption, and using fluent commercial software to simulate the paraffin melting or solidification process. However, the traditional CFD method has great limitations in grid generation, boundary treatment and solid-liquid interface tracking of complex structures. As an effective numerical simulation method, lattice Boltzmann method (LBM) has unique advantages in dealing with these problems due to its mesoscopic physical background, which used in the fields of porous media flow [18], heat transfer and solid-liquid phase transition [19] widely. Therefore, it is very suitable for the simulation of complex solid-liquid phase transition problems.

The first enthalpy-based LB model for solid-liquid phase change was introduced by Jiaung *et al.* [20], which the latent heat term was added to the temperature distribution function evolution equation and determined the position of phase transition interface by liquid fraction. Dadvand *et al.* [21] simulated the natural-convection heat transfer process in a square enclosure with discrete heat sources through the LBM. Rui *et al.* [22] calculated the 2-D natural-convection melting process in a square cavity under four different mixed boundary conditions by using the enthalpy-based LB model and pseudo potential model to track the solid-liquid interface. Hu *et al.* [23] proposed a 3-D LB model to solve the 3-D natural-convection problem with solid-liquid phase transition, including simulation of melting in a cubic cavity, convective melting in a rectangular inner cylinder enclosure and solid sphere melting in a cubic enclosure. Lin *et al.* [24] used LBM to simulate the complex interaction of natural-convection and melting of n-octadecane as PCM in spherical capsules with different sizes. Yip *et al.* [25] used the LB model with double distribution and multiple relaxation time to study the flow dynamics of natural-convection in the process of paraffin melting using inserts with different inclination angles and positions.

To sum up, a lot of researches on the heat transfer of solid-liquid PCM were studied, such as rectangular cavity, cylindrical cavity and spherical cavity. However, the authors are more interested in using the PCM which are pure materials or nanoparticles. The wide phase change temperature region of solid-liquid mixing in the phase changes process [15] is not considered. To our knowledge, the mesoscopic study considering the filling of the circular tube as a mixture has not been reported. Therefore, a double distribution enthalpy-based LB model is established in this paper. The temperature field and the flow field of paraffin wax melting process in a circular pipe are calculated by using FORTRAN language programming. The influence of different Rayleigh and Prandtl numbers on paraffin wax melting heat transfer and phase transformation process is analyzed. The mechanism analysis is helpful to provide more accurate micro-scale phase changes information for paraffin melting process, which provides some reference and guidance for energy storage of PCM and pipe-line paraffin removal.

Method and materials

Physical model

The physical model used in the numerical simulation is a 2-D circular tube. Figure 1 is a schematic diagram of paraffin melting in a circular tube. Assuming that the tube is filled with paraffin and evenly distributed, and ignoring the axial heat transfer of the tube, the heat transfer of the tube and paraffin is simplified as a 2-D heat transfer problem, and the center of the tube is regarded as the co-ordinate origin. The inner diameter of the tube is R, the initial temperature of paraffin in the tube is T_h, and the wall temperature of the tube is T_w. Different from pure substances, the paraffin is a mixture of complex components. The melting of paraffin occurs in a certain temperature range, and the phase transition temperature is not fixed. Therefore, the melting process of paraffin can be divided into solid zone, fuzzy zone and liquid zone. The T_s and T_ℓ correspond to the temperature at the beginning of melting and the temperature at the end of melting, respectively.

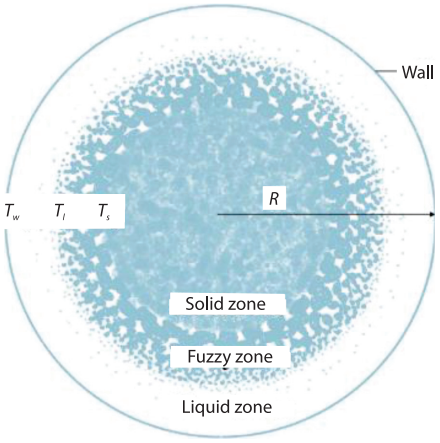

Figure 1. Physical model

Mathematical model

Governing equations

Assuming that liquid paraffin is an incompressible fluid and the viscous heat dissipation in the flow of liquid paraffin is neglected, the governing equations of liquid phase flow of paraffin melting in tube based on Boussinesq hypothesis are [26]:

$$\nabla\vec{u} = 0 \tag{1}$$

$$\frac{\partial\vec{u}}{\partial t} + (\vec{u}\nabla)\vec{u} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\vec{u} + \vec{F} \tag{2}$$

where $\vec{F}$ is the total volume force source term, which is given by eq. (3). The linear and non-linear medium resistance and buoyancy are included in the source term:

$$\vec{\mathrm{F}} = -\frac{\varepsilon \nu_f}{K}\vec{\mathrm{u}} - \frac{\varepsilon F_\varepsilon}{\sqrt{K}}\left|\vec{\mathrm{u}}\right|\vec{\mathrm{u}} + \varepsilon g\beta(T - T_{\mathrm{ref}}) \tag{3}$$

The paraffin begins to melt under certain heating conditions because of the circular tube which filled with solid paraffin. The natural-convection of the liquid phase was accompanied by the melting process. Under the condition of local heat balance, the governing equation of paraffin melting heat transfer can be described:

$$\sigma\frac{\partial T}{\partial t} + \vec{\mathrm{u}}\nabla T = \nabla(\alpha\nabla T) - \frac{L_a}{c_{p,f}}\frac{\partial \gamma_f}{\partial t} \tag{4}$$

Because the melting temperature and liquid holdup are coupled with each other, the enthalpy method is used to solve the fuzzy region of melting and the temperature of paraffin wax are calculated:

$$H_p = C_p T + \gamma_f L_a \tag{5}$$

$$\gamma_f = \frac{Hp - H_{p,\mathrm{s}}}{H_{p,\ell} - H_{p,\mathrm{s}}} \tag{6}$$

Lattice Boltzmann model

The double distribution function model is solved based on the LBM in this paper. The single relaxation time LB model is proposed by Guo *et al.* [27] can be used to simulate the velocity field of paraffin melting process and natural-convection coupled heat transfer. The density distribution function f_i and the corresponding equilibrium distribution function f_i^{eq} are expressed:

$$f_i\left(\vec{\mathrm{r}} + e_i\Delta t, t + \Delta t\right) - f_i(\vec{\mathrm{r}}, t) = -\frac{1}{\tau_f}\left[f_i(\vec{\mathrm{r}}, t) - f_i^{\mathrm{eq}}(\vec{\mathrm{r}}, t)\right] + \Delta t F_i \tag{7}$$

$$f_i^{\mathrm{eq}} = w_i\rho\left[1 + \frac{3e_i u}{c^2} + \frac{9(e_i u)^2}{2\varepsilon c^4} - \frac{3u^2}{2\varepsilon c^2}\right] \tag{8}$$

where $f_i(\vec{\mathrm{r}}, t)$ is the density distribution function which related to the velocity of position and time, $\vec{\mathrm{r}}$ – the position of the space vector, ε – the porosity of porous medium, in which $\varepsilon = 0$ is regarded as solid phase zone, in which $\varepsilon = 1$ is regarded as liquid phase zone, and $0 < \varepsilon < 1$ is regarded as the fuzzy zone.

The evolution equation of temperature distribution function proposed by Gao *et al.* [26] for the melting process of porous media is adopted in this paper, which can be described:

$$g_i\left(\vec{\mathrm{r}} + e_i\Delta t, t + \Delta t\right) - g_i\left(\vec{\mathrm{r}}, t\right) = -\frac{1}{\tau_T}\left[g_i\left(\vec{\mathrm{r}}, t\right) - g_i^{\mathrm{eq}}\left(\vec{\mathrm{r}}, t\right)\right] + \Delta t S_i \tag{9}$$

$$g_i^{\mathrm{eq}} = w_i T\left[1 + 3\frac{e_i u}{c^2\sigma} + 4.5\frac{(e_i u)^2}{c^4\sigma^2} - 1.5\frac{u^2}{c^2\sigma^2}\right] \tag{10}$$

where σ is effective heat capacity and given by $\sigma = \gamma\sigma_{f,\ell} + (1 - \gamma)\sigma_{f,\mathrm{s}}$. The corresponding external force term and non-linear source term are expressed:

$$F_i = w_i \rho \left(1 - \frac{1}{2\tau_f}\right)\left[\frac{3e_i F}{c^2} + \frac{9\left(uF : e_i e_i\right)}{c^4} - \frac{3uF}{c^2}\right] \tag{11}$$

$$S_i = -w_i \frac{L_a}{C_{p,f}\sigma}\frac{\left[\gamma_f\left(t+\Delta t\right) - \gamma_f\left(t\right)\right]}{\Delta t}\left[1 + \left(1 - \frac{1}{2\tau_T}\right)\frac{3e_i u}{\sigma c^2}\right] \tag{12}$$

Equation (11) is a quadratic non-linear equations of velocity since $\vec{F}$ contain the flow velocity. By solving the equations, u can be given:

$$u = \frac{V}{c_0 + \sqrt{c_0^2 + c_1 |V|}}$$

where V is the defined temporary velocity expressed

$$V = \sum_i e_i f_i / \rho + \frac{\Delta t}{2}\varepsilon\left[\beta g\left(T - T_{\text{ref}}\right)\right]$$

The parameters c_0 and c_1 are:

$$c_0 = \frac{1}{2}\left(1 + \varepsilon\frac{\Delta t}{2}\frac{\nu}{K}\right) \text{ and } c_1 = \varepsilon\frac{\Delta t}{2}\frac{F_\varepsilon}{\sqrt{K}}$$

In the same time step, after the migration step is completed and the temperature is obtained, and substitute the assumed liquid fraction into eq. (5) to obtain the enthalpy. The new liquid fraction is calculated by substituting the obtained enthalpy into eq. (6). The liquid fraction that meets the control accuracy can be obtained through iteration.

The dimensionless relaxation time of velocity evolution equation and temperature evolution equation in the model is determined:

$$\tau_f = \frac{3\nu_e}{\left(c^2\Delta t\right)} + 0.5 \tag{13}$$

$$\tau_T = \frac{3\alpha_e}{\left(c^2\Delta t\right)} + 0.5 \tag{14}$$

The corresponding macro parameters are defined:

$$\rho = \sum_i f_i,\ u = \sum_i \frac{e_i f_i}{\rho} + \frac{\vec{\mathrm{F}}\Delta t}{2},\ T = \sum_i g_i \tag{15}$$

Using Chapman Enskog expansion, eqs. (7) and (9) can be regressed to the corresponding macro equation.

For the LBM, the boundary conditions are very important for the accuracy and stability of the simulation results. The stepped approach method is used to construct the circular calculation domain of the circular tube section. The rebound boundary is used for the velocity boundary condition and the known temperature boundary is used for the temperature boundary condition.

Model validation

The visualization experiment of paraffin melting in the circular tube was performed in this paper. The experiment device is composed of instruments and equipment such as circular

acrylic tube, heating belt, thermocouple, thermal insulation board, digital video camera and infrared thermal imager. The circular tube used in the experiment is made of acrylic board. The inner and outer diameter of the circular tube was 61 mm and 65 mm, respectively. The circular tube wall thickness was 2 mm and the length was 160 mm. The bottom surface of one side is closed for observation, and the bottom surface of the other side is open for filling with paraffin. Before the experiment, the solid paraffin is heated to melt firstly, and then pour the melted liquid paraffin into the circular tube so that the filling is about three-quarters of the total, and it is placed horizontally to make it completely solidified at room temperature. In the experiment, the heating tape is evenly wound on the outer wall of the circular tube, and real-time feedback is provided through the thermocouple to achieve the purpose of constant temperature heating. Paraffin has an initial temperature of 20 °C, and a constant heating temperature of 52 °C is used for the outer wall of the cylinder, and the upper and lower sides are kept adiabatic. Use Nikon D7000 digital video camera and FLIR-T660 thermal imaging camera to take digital pictures and infrared thermal imaging pictures of the visualization experiment. And the schematic diagram of the experimental system is shown in fig. 2. The related physical parameters of paraffin used in the calculation are shown in tab. 1.

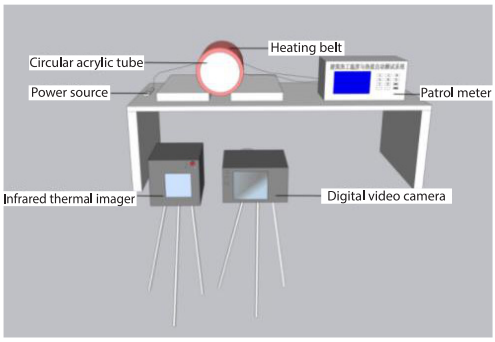

Figure 2. Schematic diagram of the experimental system

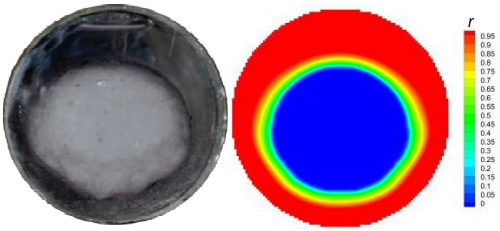

Figure 3. Phase diagram of visualization experiment and numerical calculation

The correctness of the numerical simulation results model is verified by the corresponding visual experimental results. Figure 3 shows the comparison of visualization experiment and numerical calculation phase diagram when Fo = 0.0555. It can be seen from fig. 3 that the trend of wax melting phase interface in the circular tube is close. The relative error between them is 1.27%. Table 2 shows the error comparison between the visualization experiment and the numerical calculation of the liquid fraction, which meets the accuracy requirements.

Table 1. Physical property parameters of paraffin

Physical parameters		Numerical value
Density, ρ	Liquid phase	775.09 kg/m^3
	Solid phase	880.92 kg/m^3
Specific heat capacity, C_p	Liquid phase	2800 J/kgK
	Solid phase	2250 J/kgK
Thermal conductivity, k	Liquid phase	0.15 W/mK
	Solid phase	0.25 W/mK
Kinematic viscosity, ν		$3.20 \cdot 10^{-6}$ m^2/s
Latent heat, L_a		233.5 kJ/kg
Phase transition temperature region, T_{tp}		28.0-42.0 °C

Table 2. Comparison of liquid rate error between visualization experiment and numerical calculation

Fourier number	Liquid phase rate of visualization experiment [%]	Numerical calculation of liquid phase ratio [%]	Relative error [%]
0	0.00	0.00	0%
0.00693	8.25%	12.57%	–14.77%
0.0208	19.37%	31.91%	–7.36%
0.0347	31.97%	44.18%	5.93%
0.0485	42.53%	56.42%	2.68%
0.0555	52.58%	60.92%	1.27%
0.0971	77.40%	80.10%	1.30%

Results and discussion

Temperature field and flow field

The evolution process of phase transformation and melting of paraffin in the circular tube is illustrated in fig. 4. The temperature field nephogram at 30 minutes, 40 minutes, and 60 minutes is indicated at the top, and the flow field streamline at the same time is shown at the bottom. It can be seen from fig. 4 that the circular tube filled with paraffin during the heating and melting process. The tube wall heats up to 325.15 K rapidly at the initial stage of melting ($0 < Fo < 0.027$), which results in a larger temperature difference between the tube wall and the internal paraffin. Paraffin close to the inner wall of the tube is first heated and melted, and then a thin liquid layer is formed between the paraffin and the wall. The fuzzy zone of the porous media appears slightly and the paraffin melts uniformly. The entire temperature field presents a circular symmetrical distribution. The melting process of paraffin is dominated by heating conduction at this time. At the middle stage of melting ($0.027 < Fo < 0.040$), the temperature field in the tube presents an oblong shape. Because the buoyancy force drives the liquid to rise

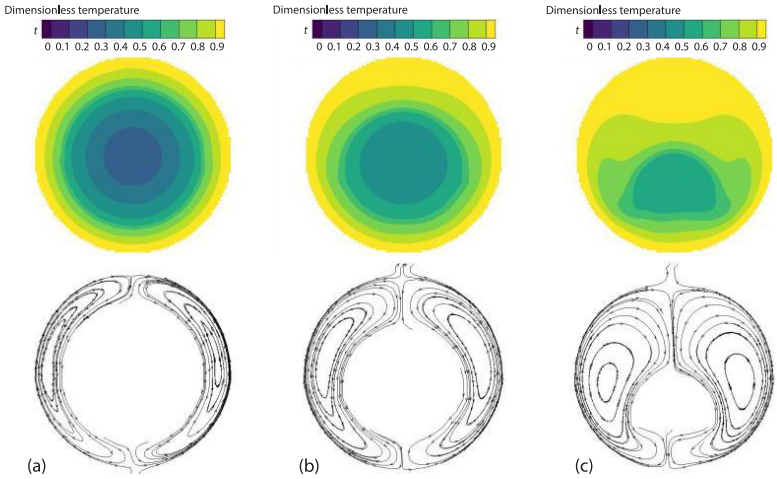

Figure 4. Distribution of temperature field and flow field at different times; (a) t = 30 minutes, Fo = 0.027, (b) t = 40 minutes, Fo = 0.040, and (c) t = 60 minutes, Fo = 0.080

during the process of paraffin melting and molten paraffin with higher temperature accumulates in the upper region. The liquid zone and fuzzy zone is thickened gradually and the natural-convection begins to appear. The vortex on both sides of the pipe is generated due to the buoyancy force drives the fluid in the pipe to move up along the pipe wall, and then the fluid descends from the center of the tube and moves in a clockwise cycle. At the later stage of melting ($0.040 < Fo < 0.080$), the natural-convection is enhanced and began to dominate. The intensity of convective heat transfer continues to increase. Paraffin continues to endothermic and melt. The temperature field presents a semicircular shape, and the solid-liquid mixing zone thickened until the paraffin is completed melted. The temperature inside the tube is closed to 325.15 K.

The effect of Rayleigh number on the melting process of paraffin

In the process of paraffin melting, the natural-convection of paraffin in the liquid zone has an important influence on the whole phase transformation process. As a dimensionless parameter to measure the strength of natural-convection, change of Rayleigh number plays an important role in the entire phase transition process. Besides, the average Nusselt number of the heated wall represents the dimensionless temperature gradient at the hot wall. The average Nusselt number on the heated wall is calculated as in [28]:

$$\mathrm{Nu} = \frac{1}{H}\int_0^H \frac{\partial}{\partial x}\left(\frac{T - T_c}{T_\mathrm{h} - T_c}\right)_{x=0} \mathrm{d}y \tag{16}$$

Figure 5 shows the variation of the average Nusselt number of the wall surface with time during the phase transformation of paraffin in the circular tube under different Rayleigh numbers. It can be observed in the figure that the average Nusselt number of the wall surface decreases sharply with the increase of the Fourier number, and then slowly decreases until it approaches zero. Therefore, in the initial stage of unsteady heat transfer ($Fo < 0.02$), which is also the initial stage of paraffin phase transformation, the heat transfer mode is mainly heat conduction at this time. There is no significant difference of Nu_{avg} under different Rayleigh numbers. The paraffin near the tube wall is heated suddenly due to the rapid heating of the outer wall of the pipe, which resulting in a larger temperature difference between the paraffin inside and the wall surface. The Nu_{avg} reaches the maximum of 8 at this moment. When the dimensionless temperature in the tube reaches 0.56, the initial temperature of wax melting is reached, and the paraffin starts to melt. The temperature gradient at the wall continues to decrease as the liquid phase area increases as time goes on. The Nu_{avg} of the corresponding wall dropped from 8 to 2 rapidly. The heat transfer mode in the tube changes from pure heat conduction natural-convection when it reaches the transition stage of the unsteady heat transfer process ($0.02 < Fo < 0.10$). The intensity of natural-convection increases with the increase of the Rayleigh number, which slows down the decrease of the number caused by the movement of the phase interface. The decrease of the Nu_{avg} is relatively slow when the $Ra = 1.0 \cdot 10^6$. There is a gentle trend appeared. Therefore, there is an intersection with $Ra = 1.0 \cdot 10^5$ and $Ra = 1.0 \cdot 10^4$. The Nu_{avg} remains near 2 at this time. Subsequently, under the strong

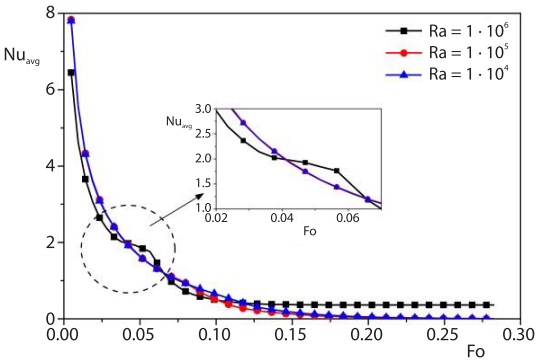

Figure 5. Variation of Nu_{avg} number of wall with time under different Rayleigh numbers

natural-convection conditions, the temperature gradient of the wall surface fluctuates slightly, and the number of Nu_{avg} dropped rapidly to produce another intersection point. The liquid zone continues to expand until all the paraffin in the tube melts at the later stage of melting (Fo > 0.10). The temperature in the tube tends to heat temperature, and the dimensionless temperature gradient of the fluid is decreased. The Nu_{avg} continues to fall and approaches zero eventually.

The effect of Prandtl number on melting process of paraffin

Prandtl number is the ratio of kinematic viscosity to thermal diffusion coefficient, which is a measure of momentum diffusion ability and thermal diffusion ability, reflecting the influence of fluid physical properties on flow and heat transfer. Under the condition of $Ra = 1.0 \cdot 10^6$, Ste = 0.482, three different conditions of Pr = 27.2, 37.2, and 47.2 are simulated and analyzed, respectively in this paper. Figure 6 shows the change of paraffin melting rate with time under different conditions. It can be observed in the figure that the corresponding time for paraffin melting rate to reach 1 is 32.98 minutes, 46.56 minutes, and 58.20 minutes under three different Prandtl numbers. It can be seen that the larger the number is, the more slowly the liquid phase fraction in the tube rises in the initial and intermediate stages of melting. Under the condition of a certain viscosity, the Prandtl number increases with the decrease of the thermal diffusion coefficient. As a result, the convective heat transfer ability is reduced and the melting proceeds more slowly, which ultimately extends the time required for the paraffin to melt completely. From the fig. 6, we can see that the difference between the longest and shortest melting time is about 25.22 min. Therefore, speed up or slow down the melting rate of paraffin in the pipe by adjusting the Prandtl number of paraffin can be met by the relevant need in engineering.

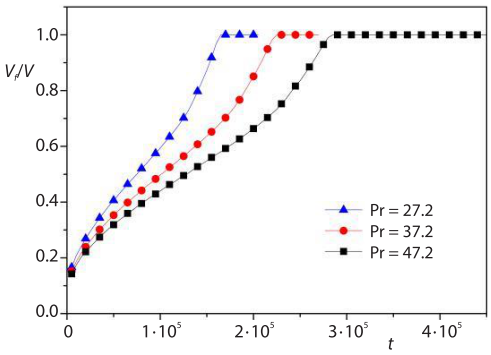

Figure 6. Variation of melting rate with time at different Prandtl numbers

Conclusions

In this paper, the melting heat transfer of paraffin in a circular tube under the action of natural-convection is simulated by considering the fuzzy zone in the process of paraffin melting based on the double distribution LBM. The following conclusions are obtained.

- For the solid-liquid phase transformation process of paraffin melting in a circular tube, heat conduction is the main factor in the initial stage of phase transformation. The existence of fuzzy zone becomes more and more obvious with the progress of melting. The role of natural-convection begins to appear and occupy a dominant position, which resulting in the asymmetry of the phase interface. Until solid paraffin in the tube is all melted into liquid. The liquid phase rate reaches the maximum, and the melting process ends at this time.
- When the Rayleigh number increases from $1.0 \cdot 10^4$ and $1.0 \cdot 10^5$ to $1.0 \cdot 10^6$, the intensity of natural-convection increases, which slows down the decrease of the Nu_{avg} caused by the movement of the phase interface. A flat area appeared during the descent. With the deepening of melting, the Nu_{avg} continues to fall and approaches zero eventually.
- The change of the Prandtl number has a significant effect on the paraffin melting phase transition process. The melting rate of paraffin is increased when Prandtl number reduced from 47.2-37.2. On the contrary, the melting rate is decreased, and the difference between the

longest and shortest melting time is about 25.22 minutes. Therefore, reducing or increasing the melting number is helpful to accelerate or weaken the melting process of paraffin, which can be adjusted according to the logarithm of demand in engineering.

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Nomenclature

c – lattice speed, [ms^{-1}]
C_p – specific heat capacity [JK^{-1}kg^{-1}]
e_i – microscopic particle velocity in each lattice
$\vec{F}$ – external force, [N]
F_ε – geometric function
f – distribution function for flow field
g – distribution function for temperature
H_p – enthalpy
K – permeability of porous media
k – thermal conductivity, [WK^{-1}m^{-1}]
L_a – latent heat of melting
Nu – Nusselt number
Pr – Prandtl number
Ra – Rayleigh number
S – source term
Ste – Stefan number
T – macroscopic temperature, [K]
t – time, [s]
Δt – time step
u – velocity in the x-direction, [ms^{-1}]
V – temporary velocity, [ms^{-1}]
w – weight function

Greek symbols

α – thermal diffusivity, [m^{2}s^{-1}]
β – thermal expansion coefficient
γ – volume fraction
ε – porosity
ν – kinematic viscosity, [m^{2}s^{-1}]
ρ – fluid density, [kgm^{-3}]
σ – thermal capacity ratio
τ – dimensionless relaxation time

Subscripts

avg – average
ℓ – liquid
s – solid
ref – reference

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