NUMERICAL STUDY ON THE EFFECT OF THERMAL DIFFUSIVITY RATIO IN PHASE CHANGE HEAT TRANSFER OF CRUDE-OIL USING LATTICE BOLTZMANN METHOD

by

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Original scientific paper
https://doi.org/10.2298/TSCI220416178L

When the long distance crude-oil pipe-line is stopped, the crude-oil will solidify gradually with the decrease of the temperature in the pipe-line. The solid-liquid thermal diffusivity can reflect the ability of heat diffusion in the phase change heat transfer process of crude-oil stop-transport. Based on the mathematical model of oil phase transition heat transfer established by enthalpy method, the lattice Boltzmann method is used to solve the governing equations of oil phase transition heat transfer. According to the simulation results, the phase change heat transfer process of crude-oil is divided into three-stages, and the mechanism of the phase change heat transfer process of crude-oil is studied. The results show that the influence of solid-liquid thermal diffusion ratio increase gradually with time. When Fourier number ≥0.043, Nusselt number and convective heat transfer intensity of mobile phase interface slightly decrease with the increase of solid-liquid thermal diffusivity ratio. The research results of this paper can provide a reference for controlling the stoppage time of pipe-line.

Key words: *crude-oil, phase change heat transfer, Lattice Boltzmann method, solid-liquid thermal diffusivity ratio*

Introduction

According to statistics, the wax content of crude-oil produced in most oilfields is more than 20% [1] according to statistics. The wax in the crude-oil will condense and deposit on the inner wall of the pipe-line [2], and the wax layer will grow towards the center of the pipe-line [3] and gradually become thicker after the pipe-line is stopped [4]. Wax is the main substance of phase transformation during the temperature drop of crude-oil [5]. Wax is the main substance of phase transition in the cooling process of crude-oil. It will lead to condensing pipe accidents [6] when the shutdown time exceeds the safe shutdown time of the pipe-line [7]. The thermal diffusivity can directly reflect the heat transfer rate. It is of great significance to study the influence of thermal diffusivity on the solidification and heat transfer of crude-oil after pipe-line closure for reasonably controlling the shutdown time and scientifically formulating the restart scheme. Therefore, it is of great significance to study the influence of thermal diffusivity on the solidifi-

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cation and heat transfer of crude-oil after pipe-line stop-transport, and to rationally control the stop-transport time and scientifically formulate the restarting plan.

Mehdi *et al.* [8] studied the heat transfer of nanofluids in tubes [9], and put forward the method to enhance the heat transfer of fluid in tubes [10] and the best working condition [11]. Liu *et al.* [12] analyzed the influence of soil thermal conductivity on the radius of the oil temperature and heat affected zone at the center of the pipe-line. Dong *et al.* [13], Zhao *et al.* [14] analyzed the influence of pipe diameter on the solidification heat transfer process of crude-oil after shutdown. Zhou *et al.* [15] proposed the influence of positive and negative crude-oil transport processes on shutdown safety events. Xu *et al.* [16] proposed the influence of changes in specific heat capacity on thermal diffusivity of crude-oil when they applied the additional specific heat capacity method to deal with latent heat source terms. Zhao *et al.* [17], Li *et al.* [18] believed that the influence of viscosity change on the temperature field of crude-oil could be ignored, and its influence on the solidification of waxy crude-oil was greater than that of specific heat capacity. Rossi di Schio *et al.* [19] studied the influence of pipe-line burial depth and Darcy-Rayleigh number on pipe-line heat transfer. Cheng *et al.* [20] believed that the increase of initial oil temperature could increase the radius of the heat-affected zone of the pipe-line. Zhao *et al.* [17], Cheng *et al.* [20] studied the influence of atmospheric temperature on pipe heat transfer. Liu *et al.* [21] conducted transient numerical study on the melting process of waxy crude-oil paste under different water temperature and flow conditions. Mahdi *et al.* [22] studied the paraffin phase transformation process of conical and cylindrical coils heated. Abdulrahman *et al.* [23] explored the influence of different Reynolds number, Re, on paraffin phase transformation in triangular cavities. Wang *et al.* [24] established a mathematical model of oil pipe-line shutdown with phase change insulation layer, and explored the influence of various factors on pipe-line insulation.

It can be seen that previous scholars mainly studied the influence of single physical property parameters on the temperature field, flow field and liquid ratio field of crude-oil, and also studied the phase transition process of wax the main phase change material in crude-oil. The physical property parameters of crude-oil cross influence each other in the process of stopping transmission and cooling of hot oil pipe-line, so a single physical property parameter cannot independently characterize the strength of natural-convection of crude-oil. In previous studies, few scholars have analyzed the influence of solid-liquid thermal diffusivity on the heat transfer process of crude-oil in stop-transport pipe-lines. However, the solid-liquid thermal diffusivity can reflect the heat diffusion ability of crude-oil in the heat transfer process, which is one of the influencing factors of the stop-transport heat transfer process, and is an important parameter in the unsteady heat conduction process.

The independence of the solid-liquid thermal diffusivity ratio as a dimensionless number can effectively eliminate the influence of the correlation of physical parameters in the unsteady heat transfer process of crude-oil. The solid-liquid thermal diffusivity ratio is selected as the variable to study the phase transition process of crude-oil stop-transport, which is conducive to the analysis of the heat transfer mechanism of thermal properties on the process of crude-oil solidification.

Crude-oil is a mixture of many components. The energy equation is usually calculated by effective thermal conductivity and effective specific heat capacity if the solid-liquid phase Lattice Boltzmann model based on enthalpy method has a multicomponent system. Gaedtke *et al*. [25] used lattice Boltzmann method (LBM) to simulate paraffin melting process with metal foam skeleton. Xu *et al*. [26] utilized the multi-component enthalpy Lattice Boltzmann model to explore the change of solid volume fraction of droplet solidification with Fourier number, Fo, at different contact angles. Lu *et al*. [27] utilized enthalpy Lattice Boltzmann model to simulate the melting process of phase change materials under different heating modes, and explored the influence of Rayleigh number, on the melting process. Zhao *et al*. [28] proposed a generalized double relaxation time Lattice Boltzmann model suitable for solid-liquid phase change of thermally heated physical properties. Han *et al*. [29] analyzed the influence of dispersion, volume fraction and diffusion direction of metal particles on the thermal performance of phase change material. Mahmoud *et al*. [30] constructed the alloy porous medium matrix in the oblique elliptic ring, and the phase change material was ice. The effective thermal diffusion coefficient and effective specific heat capacity were used to uniformly calculate the energy equation of the two-phase change regions.

It can be seen from the existing literature that previous scholars mainly applied LBM based on enthalpy method to the field of phase change energy storage. Its application in the field of phase change heat transfer of crude-oil has not been reported. Moreover, few scholars used LBM to explore the influence of solid-liquid thermal diffusivity ratio on phase transition heat transfer. Lattice Boltzmann equation is a dimensionless equation. The solid-liquid thermal diffusivity ratio is a dimensionless number. The LBM based on enthalpy method is used to solve the control equation of oil phase change heat transfer in this paper. The thermal process of phase change of crude-oil is divided into three-stages. The mechanism of phase change heat transfer of crude-oil by solid-liquid thermal diffusivity ratio is studied. The influence of natural-convection on the solidification process of crude-oil is analyzed by the change of Nusselt number, Nu, at the interface of moving phase and the change of solid-liquid thermal diffusivity. This study can provide reference for the control of pipe-line shutdown time.

Method and materials

Physical model

Figure 1 shows the oil solidification diagram of 2-D cylindrical cross-section. Assuming that the cylindrical cavity is filled with uniformly distributed oil, and the axial heat transfer of the pipe-line is ignored. The crude-oil in the pipe-line will continue to dissipate heat to the outside when the ambient temperature is lower than the initial oil temperature, causing the phase change of liquid crude-oil, and the condensate layer gradually grows to the center of the pipe-line. They are liquid zone, phase change zone and solid zone from inside to outside. The temperature of liquid crude-oil is T_h, the wax evolution point of crude-oil is T_l, the freezing point is T_s, and the inner wall temperature of the pipe-line is T_w. The inner diameter R of the pipe is 159 mm. The darcy flow generated by the waxy network is ignored and the phase change zone is regarded as the multi-phase flow zone driven by natural-convection. The heat transfer between liquid phase region and phase transition region is carried out by thermal convection, while the heat transfer between crude-oil in solid phase region is carried out by thermal conduction. Convective heat transfer occurs between the phase transition zone and the solid phase zone, and the inner wall temperature of the pipe-line is constant.

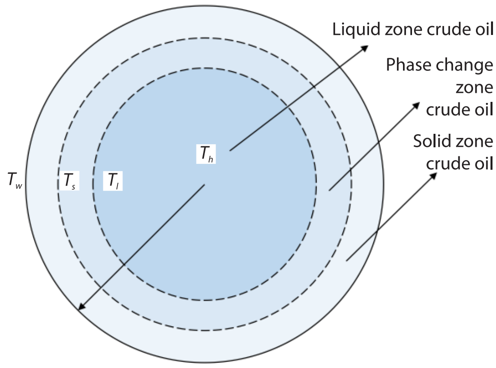

Figure 1. The 2-D cylindrical cross-section oil solidification diagram

Mathematical model

Macro control equations

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

$$\frac{\partial\vec{u}}{\partial t} + (\vec{u}\nabla)\vec{u} = -\nabla p + \nu\nabla^2\vec{u} - g\beta(T - T_m) \tag{2}$$

$$\frac{\partial T}{\partial t} + \vec{u}\nabla T = \alpha\nabla^2 T - \frac{L_a}{C_l}\frac{\partial f_l}{\partial t} \tag{3}$$

Equation (1) is the continuity equation and eq. (2) is the momentum equation. The pressure, viscous stress and buoyancy of wax are considered on the right side of the momentum equation. Equation (3) is the energy equation. Where $\vec{u}$, T, and p are the flow rate, temperature, and pressure of the fluid. The ν, C_l, and L_a are kinematic viscosity, specific constant pressure heat capacity, and latent heat of phase transformation, and β, α, and f_l are expansion coefficient, thermal diffusivity, and liquid ratio.

Lattice Boltzmann double distribution function model

The velocity field is described by the density distribution function and the temperature field is described by the temperature distribution function. A double distribution function model based on enthalpy method was established. The evolution equation of density distribution function adopts lattice Bhatnagar-Gross-Krook (BGK) double distribution function model [31]:

$$f_i(r + e_i\Delta t, t + \Delta t) - f_i(r,t) = -\frac{1}{\tau_f}\left[f_i(r,t) - f_i^{\mathrm{eq}}(r,t)\right] + \Delta t F_i \tag{4}$$

$$f_i^{\mathrm{eq}} = \omega_i\rho\left[1 + 3\frac{e_i u}{c^2} + 4.5\frac{(e_i u)^2}{c^4} - 1.5\frac{u^2}{c^2}\right] \tag{5}$$

$$F_i = \left(1 - \frac{1}{2\tau_f}\right)\omega_i\left[3\frac{e_i - u}{c^2} + 9\frac{e_i u}{c^4}e_i\right]\left[\beta g(T - T_m)\right] \tag{6}$$

The evolution equation of temperature distribution function is established using LBM of non-linear convection-diffusion equation [32]:

$$g_i(r + e_i\Delta t, t + \Delta t) - g_i(r,t) = -\frac{1}{\tau_T}\left[g_i(r,t) - g_i^{\mathrm{eq}}(r,t)\right] + \Delta t S_i \tag{7}$$

$$g_i^{\mathrm{eq}} = \omega_i T\left[1 + 3\frac{e_i u}{c^2} + 4.5\frac{(e_i u)^2}{c^4} - 1.5\frac{u^2}{c^2}\right] \tag{8}$$

$$S_i = -\omega_i\frac{L_a}{C_l}\frac{f_l(t + \Delta t) - f_l(t)}{\Delta t}\left[1 + \left(1 - \frac{1}{2\tau_T}\right)\frac{3e_i u}{c^2}\right] \tag{9}$$

where f_i and f_i^{eq} are density distribution function and equilibrium distribution function, g_i and g_i^{eq} – the distribution function and equilibrium distribution function of temperature, r – the space vector position, e_i – the lattice discrete velocity, t – the time, Δt – the time step, τ_f and τ_T – the dimensionless relaxation time of density and temperature distribution function, F_i – the external force, ω_i – the weight coefficient, T – the temperature, S_i – the source term, u – the velocity, $c = \Delta x/\Delta t$ – the lattice velocity, ρ – the density, and Δx – the lattice step.

Equations (4) and (7) can be regressed to the control eqs. (1)-(3) of phase change heat transfer of crude-oil by Chapman-Enskog expansion.

The dimensionless relaxation time required by the evolution equation of density and temperature distribution function is:

$$\tau_f = \frac{3\nu}{(c^2 \Delta t)} + 0.5 \tag{10}$$

$$\tau_T = \frac{3\alpha}{(c^2 \Delta t)} + 0.5 \tag{11}$$

The variable relaxation time is used to study the problem of heated physical properties. The relaxation time should be controlled between (0.5, 2) as far as possible [33] for the convenience of calculation. The relaxation time of the evolution equation of the temperature distribution function in the phase change area is determined by the expression proposed by Jiaung [34]:

$$\tau = \frac{1}{2} + \frac{\alpha_l}{\alpha_s}\left(\tau_s - \frac{1}{2}\right) f_l \tag{12}$$

where α_l, α_s are thermal diffusivity of liquid and solid phases, τ_s – the dimensionless relaxation time of the evolution equation of temperature distribution function of solid phase crude-oil, and f_l – the liquid ratio of the node. The transition from the current state of the fluid to the equilibrium state can be regarded as a relaxation process by the BGK approximation. The relaxation time in the phase change zone is inversely proportional to the ratio of solid-liquid thermal diffusivity according to eq. (12). The relaxation time indicates the rate at which the fluid returns to equilibrium. The change of the solid-liquid thermal diffusivity ratio can directly reflect the velocity of fluid returning to equilibrium state and indirectly reflect the time of crude-oil reaching solidification state. It is of great significance to analyze the influence of solid-liquid thermal diffusivity ratio on phase transition heat transfer of crude-oil in shutdown pipe-line.

Initial and boundary conditions

The initial temperature of crude-oil is 298.15 K. The constant temperature of pipe wall was 273.15 K. Lattice Boltzmann equation is a dimensionless equation, also to make the simulation results more universal. We convert the actual temperature to a dimensionless temperature. The conversion formula:

$$T^* = \frac{T - T_f}{T_0 - T_f} \tag{13}$$

where T^* is the dimensionless temperature after conversion, T – the actual temperature, and T_f – the constant temperature of the tube wall. The initial and steady-state dimensionless temperatures of crude-oil after dimensionless treatment are 1.0 and 0.0. The temperature range of dimensionless phase transition of crude-oil is 0.4-0.8 through the conversion of crude-oil physical parameters.

Planck constant, $\hbar$, was 33.02. Stefan number, Ste, was 5.517. The Rayleigh number was 1.0×10^6 through the conversion of crude-oil physical parameters. The actual time $t = t'/15.6$ is obtained by satisfying the equality of the actual and lattice numbers. The t' is the simulated time step.

Model verification

The grid of 100 × 100 simulation can meet the accuracy requirements after verification. Due to the deep color of crude-oil, it is difficult to accurately determine the completion of solidification by existing technical means. Wax is the main substance in the phase change of crude-oil. The visualization experiment of wax solidification in cylindrical cavity verifies the validity of lattice Boltzmann double distribution model. Due to the wide range of phase change temperatures of wax, we heated the initial temperature of the wax above 60 °C to ensure that the initial wax is all liquid. The experimental device is shown in fig. 2. Liquid wax was filled in the cylindrical cavity used in the experiment. Liquid wax was filled in a cylindrical chamber. The wax in the cylindrical cavity was cooled at a constant temperature in the experiment, and the temperature was measured with a thermocouple. Digital image is captured using Nikon D7000 digital camera.

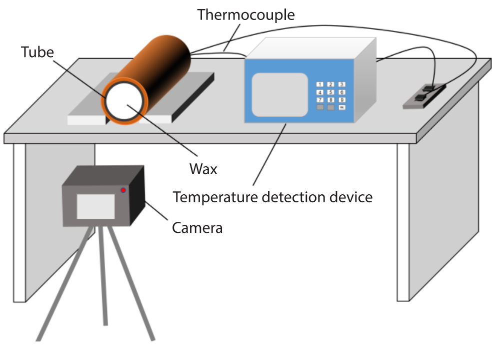

Figure 2. Experiment device

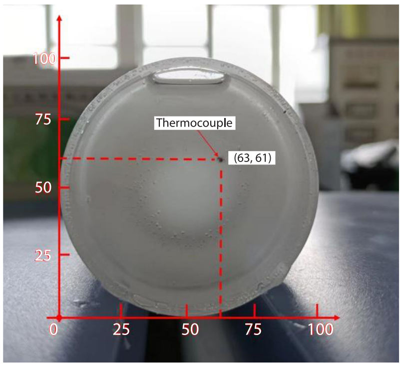

Figure 3. The location of random temperature point (63.61)

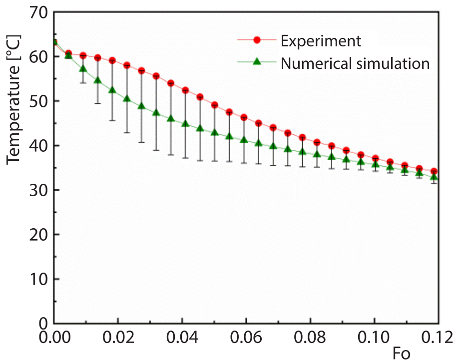

Figure 4. Temperature varies with different Fourier numbers at a certain point (63.61)

We randomly selected temperature points in order to avoid the influence of temperature changes of specific points on the experiment. The co-ordinates were put into the program for simulation calculation. Figure 3 shows the location of random temperature point (63.61).

Table1. Temperature error between simulation and experiment at a certain point with different Fourier numbers

Serial number	Fo	Simulate temperature [°C]	Experimental temperature [°C]	Error
1	0.0047	62.56	60.70	–2.90%
2	0.0125	58.69	59.90	2.02%
3	0.0376	45.74	53.60	14.66%
4	0.0719	39.44	43.20	8.70%
5	0.1060	35.17	36.00	2.30%
6	0.1180	32.61	34.20	4.64%

The temperature drop curve at a certain point (63.61) in the simulation and experimental process is shown in fig. 4. The simulated temperature drop curve is basically consistent with the experimental temperature drop curve when Fourier number, Fo, is greater than 0.1. The error analysis was performed on simulated and experimental temperatures with different Fourier numbers as shown in tab. 1. The maximum error is 14.66%, the minimum error is 2.02%, and the error range is within 15%, which meets the requirements of engineering accuracy and the model is correct.

Results and discussion

Mechanism of phase change heat transfer in shutdown crude-oil

Figure 5 shows the transient temperature field of crude-oil with different Fourier numbers. Figure 6 shows the transient flow field with different Fourier numbers. The transient liquid ratio field with different Fourier numbers is shown in fig. 7. It can be seen from figs. 5-7 that the solidification heat transfer process of stopping pipe-line can be divided into three-stages according to the change of Fourier number. The natural-convection of liquid crude-oil is strong when Fo = 0.0024, and the temperature field of crude-oil becomes *pear shape* due to the interference of flow field. The main way of heat transfer is natural-convection in the first stage of heat transfer. The continuous natural-convection makes the shape of the high temperature region appear *arc-shaped* when Fo = 0.0085. The main way of heat transfer is natural-convection and heat conduction in the second stage of heat transfer. The condensate layer thickens and the role of heat conduction becomes prominent gradually when the Fourier number increases to 0.0169. The condensate layer has covered most of the section of the pipe-line when the Fourier number increases to 0.0339. The crude-oil heat transfer mode is approximately pure heat conduction at this time in the third stage of heat transfer, until the condensate layer covers all the section of the pipe-line.

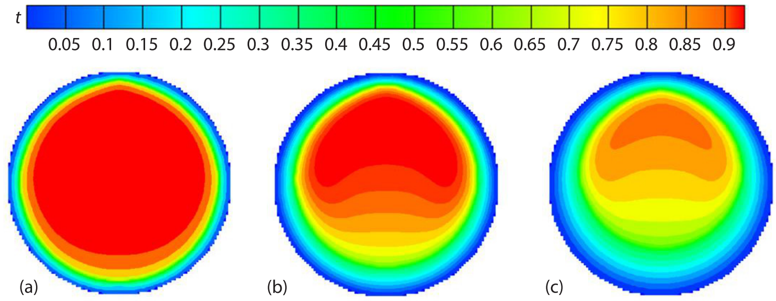

Figure 5. Transient temperature field of crude-oil with different Fourier numbers; (a) Fo = 0.0024, (b) Fo = 0.0085, and (c) Fo = 0.0169

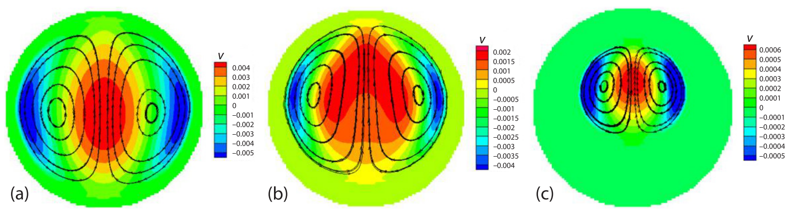

Figure 6. Transient flow field of crude-oil with different Fourier numbers; (a) Fo = 0.0024, (b) Fo = 0.0085, and (c) Fo = 0.0339

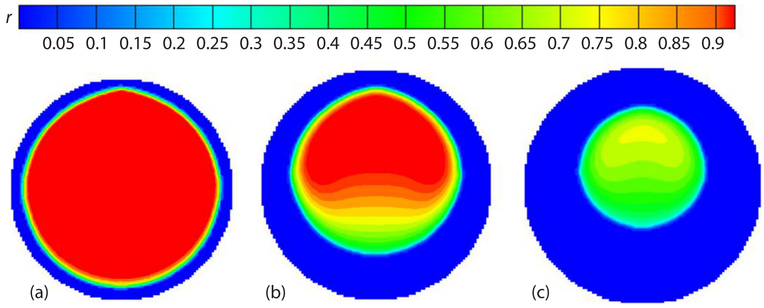

Figure 7. Transient liquid ratio field of crude-oil with different Fourier numbers; (a) Fo = 0.0024, (b) Fo = 0.0169, and (c) Fo = 0.0339

The influence of solid-liquid thermal diffusivity ratio on crude-oil phasetransformation

The influence of solid-liquid thermal diffusivity ratio on crude-oil temperature field

It is assumed that the physical property parameters of crude-oil in the phase transformation zone change with temperature or liquid ratio in this paper, and the thermal diffusivity ratio of solid and liquid crude-oil is selected as variable parameter. The thermal diffusivity ratio of crude-oil is adjusted by changing the thermal diffusivity of solid crude-oil. The solid-liquid thermal diffusivity ratio of crude-oil was calculated as 1.2 through the calculation of crude-oil physical properties. The solid-liquid thermal diffusity ratio were selected as 1.0, 1.2, and 1.4 to study the influence of the change of solid-liquid thermal diffusivity ratio on the phase change process of shut-down crude-oil.

Figure 8 shows the transient temperature field evolution of crude-oil under different solid-liquid thermal diffusivity ratios. It is known that the nodes with dimensionless temperature below 0.4 are located in the solid phase zone. Nodes with dimensionless temperature higher than 0.8 are located in the liquid zone. The nodes with a dimensionless temperature of 0.4-0.8 are located in the phase change zone. As shown in figs. 8(a) and 8(d): the temperature field

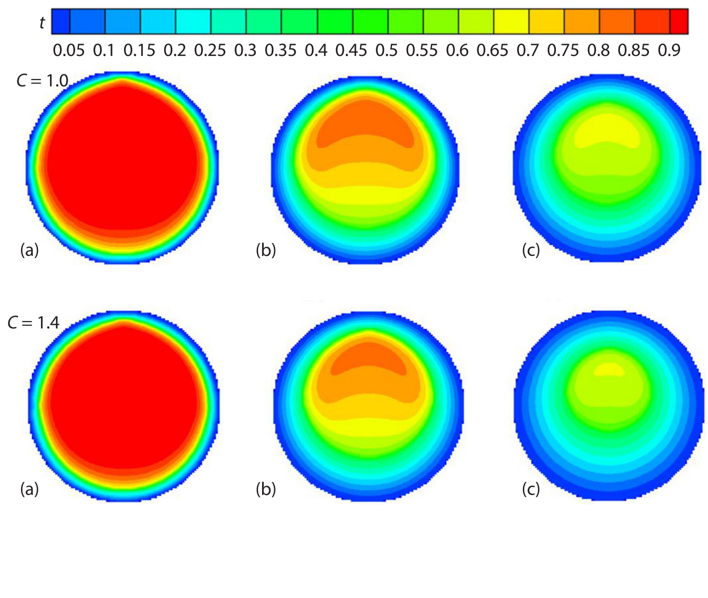

Figure 8. Evolution of transient temperature field of crude-oil with different solid-liquid thermal diffusivity ratios; (a) Fo = 0.0024, (b) Fo = 0.0169, (c) Fo = 0.0339, (d) Fo = 0.0024, (e) Fo = 0.0169, and (f) Fo = 0.0339

of crude-oil dominated by natural-convection is slightly affected by the solid-liquid thermal diffusivity ratio when the solid-liquid thermal diffusivity ratio, *C*, increases from 1.0-1.4, the isotherms of crude-oil in the phase change zone at the bottom of the pipe-line become slightly denser. It can be seen from figs. 8(b) and 8(e) that the temperature field of crude-oil in the second stage of heat transfer varies little. The thickness of condensate layer near the tube wall becomes larger at this time, the area of phase change zone and liquid phase zone of crude-oil shrinks slightly. The maximum dimensionless temperature remains unchanged. It can be seen from Figures 8(c) and 8(f) that the temperature field of crude-oil in the third stage of heat transfer is greatly affected. The condensing layer near the pipe wall is obviously thickened, which leads to a significant in a significant increase of the area of pure heat conduction zone and a significantly smaller area of phase change zone.

The influence of solid-liquid thermal diffusivity ratio on pipe-line section vertical temperature

The temperature field in the first stage of crude-oil heat transfer is almost not affected by the solid-liquid thermal diffusivity ratio, is shown in fig. 9. Therefore, the vertical non-dimensional temperature of pipe-line section at a certain time in the second and third stages of crude-oil heat transfer is selected as the research object. The variation trend of crude-oil non-dimensional temperature in the vertical direction of pipe-line section with Fourier number under different solid-liquid thermal diffusivity ratios are shown in fig. 9 in the second and third stages.

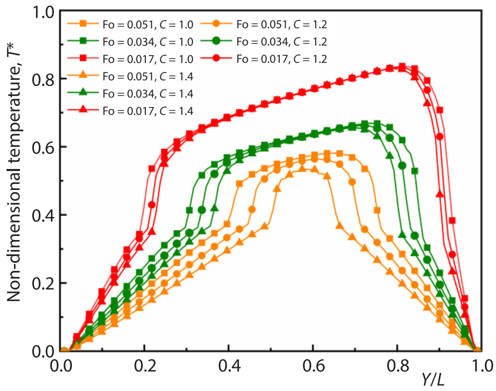

Figure 9. Temperature evolution in the vertical direction of the pipe section under different solid-liquid thermal diffusivity ratios

It can be seen from fig. 9 that the thickness of the condensate layer is not obvious in the area with dimensionless temperature below 0.4 when Fo = 0.017. The isotherm shifts slightly to the center of the pipe-line with the increase of solid-liquid thermal diffusivity ratio. The oil temperature in the region close to the condensate layer is disturbed, and the isotherm shifts slightly to the center of the pipe-line in the non-dimensional phase transition zone with 0.4-0.8 temperature, while the oil temperature in the region in contact with the liquid phase zone is almost unaffected by the solid-liquid thermal diffusivity ratio. The temperature of crude-oil is almost unaffected by the solid-liquid thermal diffusivity ratio in the non-dimensional liquid zone of 0.8-1.0. The maximum dimensionless temperature of crude-oil is about 0.65 when the Fourier number increases to 0.034. The inward migration of isotherm caused by the increase of solid-liquid thermal diffusivity is more obvious in the solid zone, and so is the temperature change of crude-oil in the phase change zone in contact with the solid zone. The crude-oil in the phase change zone with a dimensionless temperature higher than 0.6 is almost unaffected by the thermal diffusivity ratio between solid and liquid. The isotherm of the condensate layer and the crude-oil in the phase change zone shifts inward greatly when the Fourier number increase to 0.051 with the increase of solid-liquid thermal diffusivity ratio. The thermal diffusivity of the condensate layer determines the heat transfer rate of the whole crude-oil at the moment. It can be seen that the change of solid-liquid thermal diffusivity ratio has little influence on the temperature of crude-oil in the liquid zone and the phase change zone with higher liquid ratio. It has a great influence on the temperature of crude-oil in the solid zone. The influence of solid-liquid thermal diffusivity ratio on the overall temperature field of crude-oil will gradually deepen with the passage of time. The disturbance caused by the increase of solid-liquid thermal diffusivity ratio on the isotherm of the condensate layer will gradually spread to the crude-oil in the phase change zone, thus affecting the crude-oil temperature at the center point of the pipe-line in the second and third stages of crude-oil heat transfer. The aforementioned analysis shows that the solid-liquid thermal diffusivity ratio has a great influence on the temperature field in the third stage of heat transfer. The solidification rate of crude-oil is significantly accelerated, and the solid phase zone is significantly increased when the heat transfer enters the third stage. The pipe-line shutdown time should be controlled in the first and second stages of heat transfer.

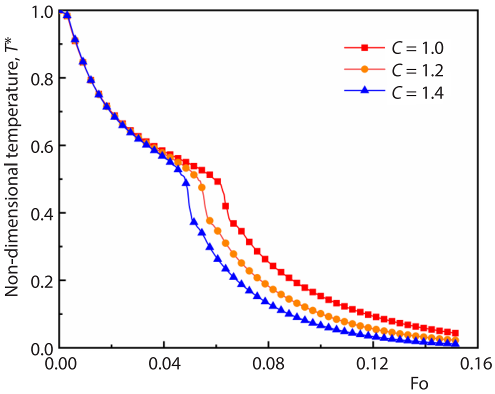

Figure 10. Oil temperature change in pipe-line center under different solid-liquid thermal diffusivity ratio

The influence of solid-liquid thermal diffusivity ratio on crude-oil temperature at pipe-line center point

The temperature drop law of crude-oil in the center of pipe-line can reflect the temperature drop process of the whole pipe-line section from the side. The mechanism of the solid-liquid thermal diffusivity ratio relative to the oil temperature at the center of the pipe-line can be analyzed from the whole process of temperature drop during shutdown by selecting the oil temperature at the center of the pipe-line as the research object. Figure 10 shows the variation trend of oil non-dimensional temperature at the center point of pipe-lines with different solid-liquid thermal diffusivity ratios.

It can be seen from fig. 10 that the oil temperature at the center point of the pipe-line does not change significantly with the increase of the solid-liquid thermal diffusivity ratio when Fo < 0.025. The condensate layer has covered most of the section of the pipe-line after entering the third stage of crude-oil heat transfer. The liquid zone of crude-oil has disappeared, and the flow zone is occupied by the phase change zone at this time. It can be seen from fig. 10 that the influence of solid-liquid thermal diffusivity ratio on the crude-oil temperature in the phase change zone begins to emerge in the third stage of heat transfer. The oil temperature at the center point of the pipe is disturbed when the crude-oil in the pipe-line is in the third stage of heat transfer. The oil temperature at the center of the pipe-line gradually decreases with the increase of the solid-liquid thermal diffusivity ratio at this moment, which has little influence on the temperature field of the crude-oil in the phase zone, and the liquid crude-oil is almost unaffected. It can be seen that the oil temperature at the center point of the pipe-line is less affected by the solid-liquid thermal diffusivity ratio in the first and second stages of crude-oil heat transfer. The oil temperature at the central point of the pipe-line is greatly affected by the solid-liquid heat diffusion ratio in the third stage of crude-oil heat transfer. The pipe-line shutdown time needs to be controlled in the first and second stages of heat transfer to avoid excessive condensation of crude-oil.

The influence of solid-liquid thermal diffusivity ratio on Nusselt number at mobile phase interface

Nusselt number at the junction between the phase change zone and the solid zone was selected as the research object to explore the influence of the solid-liquid thermal diffusivity ratio on Nusselt number at the moving phase interface. The Nusselt number on the mobile phase interface can accurately describe the convective heat transfer intensity between crude-oil and mobile phase interface, and thus reflect the influence of the solid-liquid thermal diffusivity on the convective heat transfer of crude-oil in the shutdown pipe-line.

The changing trend of Nusselt number at the mobile phase interface of crude-oil under different solid-liquid thermal diffusivity ratio is shown in fig. 11. The abscissa is Fourier number, the ordinate is the average Nusselt number of moving phase interface (Nu_{avg}), and C is the solid-liquid thermal diffusivity ratio. Since the solidification time of crude-oil under different C is different, the Fourier number corresponding to Nu_{avg} at the end point of different curves is different. Figure 11 tells that Nu_{avg} hardly changes with the increase of solid-liquid thermal diffusivity ratio when $0.00 < Fo < 0.043$. It is in the late stage of the third stage of crude-oil heat transfer when $Fo = 0.043$, $Nu_{avg} = 7.51$. It can be seen from fig. 11 that the isotherms of crude-oil in the solid zone and phase change zone shift to the tube with the increase of Fourier number, and the surface temperature of the condensate layer is almost unchanged at this time. However, the temperature of crude-oil in phase change zone in contact with the condensate layer decreases obviously, which makes the temperature gradient of the interface between the two decrease. The Nu_{avg} starts to decrease with the increase of Fourier number and solid-liquid thermal diffusivity ratio. The solid-liquid thermal diffusivity ratio has little effect on the surface temperature of condensate layer in the whole process of temperature drop of crude-oil. The solid-liquid thermal diffusivity ratio has little effect on the crude-oil temperature in the phase change zone in contact with the condensate layer when $Fo < 0.043$. It can be seen from fig. 11 that Nu_{avg} is almost not affected by the solid-liquid thermal diffusivity ratio, and the convective heat transfer intensity is almost not affected by the solid-liquid thermal diffusivity ratio when $Fo < 0.043$. The number of Nu_{avg} decreases slightly and the convective heat transfer intensity decreases slightly with the increase of solid-liquid thermal diffusivity ratio when $Fo \geq 0.043$.

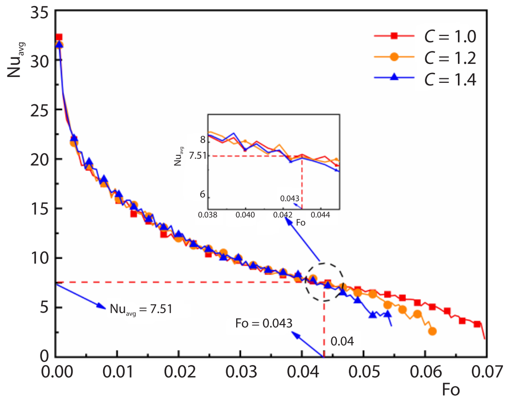

Figure 11. Nusselt number changes of crude-oil mobile phase interface with different solid-liquid thermal diffusivity ratio

Conclusion

The effect of thermal diffusivity ratio on phase transition heat of crude-oil is discussed in this paper. The results showed that with the increase of the solid-liquid thermal diffusivity ratio from 1.0-1.4, the condensate layer of crude-oil thickened obviously, indicating that the increase of the solid-liquid thermal diffusivity ratio significantly accelerated the solidification rate of crude-oil. After improving the position of Nusselt number calculation, Nusselt number at the mobile phase interface was used to describe the influence of thermal physical properties on crude-oil solidification. When $0.00 < Fo < 0.043$, Nu_{avg} almost has no change with the increase of solid-liquid thermal diffusivity ratio. When $Fo \geq 0.043$, the local Nusselt number and convective heat transfer intensity decreased slightly with the increase of the solid-liquid thermal diffusivity ratio. In the first and second stages of oil heat transfer, the solid-liquid thermal diffusivity ratio had little influence on oil temperature field, flow field and liquid rate field. The influence of solid-liquid thermal diffusion ratio increased gradually with time.

In order to avoid the phenomenon that the pipe-line is difficult to restart, the pipe-line stop time should avoid entering the third stage of heat transfer. By studying the influence of the solid-liquid thermal diffusivity ratio on the phase transition of crude-oil and calculating the solid-liquid thermal diffusivity ratio, the allowed stop-flow time of pipe-line can be estimated. The first and second stages of oil heat transfer can also be prolonged if the solid-liquid thermal diffusivity ratio is reduced. In future studies, we also need to consider the non-Newtonian fluid characteristics of crude-oil to make the simulation closer to reality.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (No. 52076036), Heilongjiang Province Natural Science Foundation Project (No. LH2020E017).

Nomenclature

C – solid-liquid thermal diffusivity ratio
C_l – specific heat capacity at constant pressure
c – lattice speed, [ms^{-1}]
c_p – specific heat capacity, [JK^{-1}kg^{-1}]
e_i – microscopic particle velocity in each lattice
F – external force, [N]
f – distribution function for flow field
f_l – liquid fraction
g – distribution function for temperature
H_p – enthalpy
L_a – latent heat of melting
Nu – Nusselt number
R – inner diameter, [mm]
Ra – Rayleigh number
S – source term
T – macroscopic temperature, [K]
T_h –temperature of liquid crude-oil, [K]
T_s –freezing point, [K]
T_w – inner wall temperature of the pipe-line, [K]
T_l – wax evolution point of crude-oil, [K]
t – time, [s]
Δt – time step
u – velocity in the x-direction, [ms^{-1}]

Greek symbols

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

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Paper submitted: April 16, 2022
Paper revised: June 2, 2022
Paper accepted: October 11, 2022