ANALYSIS OF HEAT TRANSFER CHARACTERISTICS OF PARAFFIN OIL IN OIL TANK BASED ON THE THREE-PHASE PARTITION METHOD

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The temperature drop process of waxy crude oil in an oil tank is an unsteady natural convection process involving multi-substance coupling, multi-heat transfer coupling, phase transformation, solid-liquid interaction, rheological change, fluid-solid coupling and turbulence, and the heat transfer process is highly complicated. According to the influence of the phase change process of waxy crude oil on the heat transfer process, based on the new three-phase partition method, the phase change heat transfer model of waxy crude oil in an oil tank was established, and the finite volume method was used to carry out the equation discretization and solution. Through numerical simulation, the evolution laws of the temperature field, flow field, and growth of the condensate layer during the cooling process of oil in the tank were analyzed. The results had theoretical guidance and significance for the scientific design of the oil tank's thermal insulation structure.

Key words: *oil tank, numerical simulation, three-phase partition method, phase change heat transfer*

1. Introduction

Most waxy crude oil has the characteristics of easy coagulation, high viscosity and complex rheology and usually needs heating treatment in actual production and storage. The waxy oil in the tank is cooled during storage by heat transfer to the outside world. When the oil temperature drops below the wax precipitation point, waxy crude oil begins to decompose. When the wax precipitation fraction reaches 2%~3% of the total mass of waxy crude oil, the waxy crude oil will gelate, which will seriously affect the storage safety of waxy crude oil [1-2]. Therefore, it is of great significance to study the law of temperature drop of paraffin oil in an oil tank and accurately grasp its temperature drop characteristics for the scientific design of thermal insulation structure design of oil tank, rational formulation of oil tank turnover scheme and reduction of production cost.

The phase change heat transfer process of waxy crude oil is very complicated. The natural convection effect of the crude oil will change with the phase state, and the release of latent heat of phase change is a typical nonlinear process, and its mathematical description is complicated. The phase change heat transfer model of crude oil involves three main problems, including latent heat treatment, natural convection treatment and phase interface determination [3-4].

At present, there are several different methods to deal with the latent heat of phase transition. In the early phase change heat transfer studies, the latent heat of phase change was often ignored due to its irregular release and difficulty in tracking. For example, Cheng et al. [5] established the temperature drop model of pipeline shutdown by using the apparent heat capacity method, analyzed the influence of different initial oil temperatures, different ambient temperatures and different soil thermal conductivity on the temperature field of crude oil, and tracked the solidified interface of crude oil to confirm the change rule of interface position. Liu et al. [6] proposed the estimation criterion of the total frozen amount of crude oil by tracking the trajectory of the maximum temperature point of the pipeline. Sahand et al. [7] used the fluid volume method to describe the governing equations and regarded the latent heat as a function that changed linearly with temperature and liquid rate. Wang Lu et al. [8] studied the melting characteristics of gelled crude oil heated in a cylinder vessel by experimental methods and studied the phase change heat transfer process by numerical simulation by using the additional specific heat capacity method. In this method, latent heat of phase change and explicit heat treatment were transformed into specific heat functions varying with temperature and applied in simulation calculation. The problems existing in other latent heat treatment methods were discarded, and the accuracy of the phase change model of crude oil was improved.

The density of waxy crude oil at different temperatures is different, and natural convection will occur under the action of the gravity field. In the literature [11-14], the natural convection process in the oil tank was simplified to the heat conduction process for calculation. This assumption was quite different from the actual heat transfer process of the oil tank, and the calculation error was significant. In recent years, many scholars have combined the equation of motion and the equation of energy to solve the problem of natural convection. For example, Zhao et al. [14] used CFD software to calculate and analyze the heat transfer characteristics of waxy crude oil at lower temperatures. The enthalpy-porous medium model can be used in the heat transfer model of crude oil because of the characteristics of a porous medium with the precipitation and crosslinking of wax crystals. In this model, liquid fraction is used to describe the degree of the porous medium of crude oil, and the seepage model describes the convective movement in porous medium with liquid fraction less than 1. Hu et al. [15] used the enthalpy-porous medium model to conduct a numerical simulation of the phase change heat transfer process of high-viscosity crude oil in the oil tank of a sunken ship and obtained the distribution law of temperature field in the phase change process of crude oil.

The phase change heat transfer process of crude oil is a typical Stefan heat transfer problem with a moving phase interface. According to the different phases of partitioning, the models can be divided into three categories: liquid-solid two-phase partitioning model, enthalpy porous media model, and three-phase partitioning model. The traditional two-phase partition model divides the phase transformation process of crude oil into liquid phase and solid phase. For example, Xu et al. [16] used the two-phase partition model to carry out the thermal calculation on the hot oil pipeline and simulated the temperature drop process of crude oil. The infinite thin phase interface model of two-phase partition does not consider the phase state change process of wax crystals in the process of wax precipitation and ignores the influence of porous properties of wax crystals formed after crosslinking. The enthalpy -- porous medium model proposed by Lu uses the enthalpy equation to describe the whole-phase transition heat transfer of crude oil without the need to determine the phase interface. For example, Zhou et al. [17] studied the heat storage and release laws of phase change materials at different positions in a circular tube by using the enthalpy porous medium model and the concept of liquid phase fraction. However, in the enthalpy model, the selection of phase transition temperature range was usually 1.5 ℃ above and below freezing point or from freezing point to wax precipitation point, which is not consistent with the actual temperature range of crude oil with porous medium characteristics, resulting in a specific deviation of simulation results.

In recent years, our team has proposed a new broad phase change zonal heat transfer model, also known as the three-phase zonal model, which divides crude oil in phase change into liquid region, porous medium mixed region and solid phase region [18]. The effect of the waxy crystal phase on heat transfer mode is considered in the wide-phase interface partition model. The comparison between experimental data and simulation results shows that the model describes the phase change heat transfer process of waxy crude oil more accurately.

In this paper, based on the phase-change heat transfer model of waxy crude oil in new zones, the phase-change heat transfer characteristics of crude oil in the oil tank are analyzed, and the evolution laws of temperature field, flow field and condensate layer in the oil tank are clarified by considering the influence of latent heat and natural convection of phase-change. The influence of the temperature zone of porous media on the phase change heat transfer of crude oil is deeply analyzed.

2. Establishment of physical and mathematical models

2.1. Physical model

This paper takes an equal-scale miniature oil tank as an example, and the physical model is shown in Fig. 1.

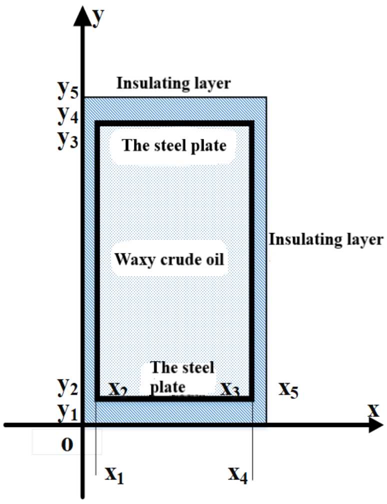

Fig.1 Physical model of crude oil tank

The oil tank is a cylinder with a diameter of 1 m and a height of 2 m. The dimensions are: x_1 = 0.04 m, x_2 = 0.05 m, x_3= 1.05 m, x_4 = 1.06 m, x_5 = 1.10 m; y_1 = 0.04 m, y_2= 0.05 m, y_3= 2.05 m, y_4 = 2.15 m, y_5= 2.55 m, and steel plate thickness D =10 mm. The model is divided into three parts: crude oil zone, steel plate layer and insulation layer. The following hypotheses are made for the research object.

1. Ignore the oil inlet of the crude oil tank and simplify the model into a cylinder;
2. Ignore the contact thermal resistance of the steel plate and insulation layer;

3. Assume that the ambient temperature is uniform and does not change;

4. There is no wax in the inner wall of the steel plate;

5. Consider the oil tank in accordance with the axis symmetry, the three-dimensional problem into a two-dimensional problem.

2.2. mathematical models

1. The oil liquid region

(a) The continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla (\rho u) = 0 \tag{1}$$

Where, ρ is the density of crude, [kgm^{-3}]. t is temperature drop time, h. u is the velocity vector, [ms^{-1}].

(b) The momentum equation

In the cartesian coordinate system, the momentum equation is described (τ is the viscous stress, F is the external force, $F_x = 0$, $F_y = -\rho g$).

$$\frac{\partial (\rho u)}{\partial t} + (\rho u \cdot \nabla) u = -(\nabla P) + (\nabla \cdot \tau) + F \tag{2}$$

$$\frac{\partial (\rho u)}{\partial t} + \nabla(\rho u \cdot u) = -\frac{\partial P}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + F_x \tag{3}$$

$$\frac{\partial (\rho v)}{\partial t} + \nabla(\rho v \cdot u) = -\frac{\partial P}{\partial y} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + F_y \tag{4}$$

$$\tau_{xx} = 2\mu \frac{\partial u}{\partial x} + \lambda \nabla(u) \tag{5}$$

$$\tau_{yy} = 2\mu \frac{\partial v}{\partial y} + \lambda \nabla(u) \tag{6}$$

$$\tau_{xy} = \tau_{yx} = \mu(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}) \tag{7}$$

$$\lambda = -\frac{2}{3}\mu \tag{8}$$

Where, P is the apparent stress, Pa. F is the effect of outside force, N. μ is the kinematic viscosity, [pa·s]; T is the crude oil temperature, K, g is the acceleration of gravity, m/s^2. λ_s is the thermal conductivity, [Wm^{-1}K^{-1}].

(c) The energy equation

The energy equation represents that the increase of energy in the control body is the sum of the heat flow and the work done by the applied force on the control body.

$$\frac{\partial (\rho c_p T)}{\partial t} + (\rho c_p u \cdot \nabla T) = \lambda_t \nabla^2 T \tag{9}$$

$$\varepsilon = 1 - \frac{T_x - T}{T_x - T_n} \tag{10}$$

$$\varphi = 1 - \varepsilon \tag{11}$$

$$\lambda_t = \lambda_l \cdot \frac{2 + \lambda_s / \lambda_l + 2\varphi(\frac{\lambda_s}{\lambda_l} - 1)}{2 + \lambda_s / \lambda_l - \varphi(\frac{\lambda_s}{\lambda_l} - 1)} \tag{12}$$

Where, c_p is the specific heat capacity of crude oil, [Jkg^{-1}K^{-1}]. λ_1 is the liquid thermal conductivity, [Wm^{-1}k^{-1}]. λ_t is the effective thermal conductivity, [Wm^{-1}k^{-1}]. λ_s is the solid phase thermal conductivity, [Wm^{-1}k^{-1}]. ε is the iquid fraction. φ is the solid fraction.

2. The crude oil porous medium area

The mathematical description of the energy equation in the porous media region in the broad phase change zonal method model is shown in Formula (9), and the momentum equation is shown in Formula (13).

$$\frac{\partial\ (\rho u)}{\partial t} + (\rho u \cdot \nabla)\frac{u}{\varepsilon} = -\nabla(\varepsilon P) + \mu_e \nabla^2 u + F \tag{13}$$

$$F = -\frac{\varepsilon\mu_e}{K} u\rho - \frac{\varepsilon F_\varepsilon}{\sqrt{K}} u|u| + \varepsilon\rho g\beta(T - T_{ref}) \tag{14}$$

$$F_\varepsilon = \frac{1.75}{\sqrt{150\varepsilon^3}} \tag{15}$$

$$K = \frac{\varepsilon^3}{C(1-\varepsilon)^2} \tag{16}$$

$$\lambda_t = (1-\varepsilon)\lambda_s + \varepsilon\lambda_l \tag{17}$$

Where, K is the permeability. F_ε is the shape factor. T_{ref} is the reference temperature of porous media, K. C is the porous media coefficient,10^5. β is the coefficient of expansion,1/K.

3. The solid region of crude oil

There is no fluid movement in the solid phase region, and the energy equation completely controls the solid phase. The mathematical description is shown in Formula (9), and its effective thermal conductivity is $\lambda_t = \lambda_s$.

4. The area outside the oil tank

The steel wall and thermal insulation layer of the oil tank are two-dimensional unsteady heat conduction, and the heat transfer equation is as follows.

$$\rho_{1p} c_{1p} \frac{\partial T}{\partial t} = \lambda_1 \left(\frac{\partial^2 T}{\partial \mathrm{x}^2} + \frac{\partial^2 T}{\partial \mathrm{y}^2} \right) \quad \begin{matrix} x_1 \le x \le x_2, x_3 \le x \le x_4; \\ y_1 \le y \le y_2, y_3 \le y \le y_4 \end{matrix} \tag{18}$$

$$\rho_{2p} c_{2p} \frac{\partial T}{\partial t} = \lambda_2 \left(\frac{\partial^2 T}{\partial \mathrm{x}^2} + \frac{\partial^2 T}{\partial \mathrm{y}^2} \right) \quad \begin{matrix} x \le x_1, x_4 \le x \le x_5; \\ y \le y_1, y_4 \le y \le y_5 \end{matrix} \tag{19}$$

Where, ρ_{1p} is the steel material density, [kgm^{-3}]. c_{1p} is the specific heat capacity of steel materials, [Jkg^{-1}K^{-1}]. λ_1 is the thermal conductivity of steel, [Wm^{-1}K^{-1}]. ρ_{2p} is the insulation material density, [kgm^{-3}]. c_{2p} is the specific heat capacity of insulation materials,[Jkg^{-1}K^{-1}]. λ_2 is the thermal conductivity of thermal insulation material, [Wm^{-1}K^{-1}].

5. Boundaries and initial conditions

The outer boundary of the insulation layer is mixed heat transfer, and the initial temperature is constant. The mathematical description is as follows.

$$-\lambda_2 \frac{dt}{dx} = h\left(T - T_f\right) \quad x = 0, x = x_3 \tag{20}$$

$$-\lambda_2 \frac{dt}{dy} = h\left(T - T_f\right) \quad y = 0, y = y_5 \tag{21}$$

$$T\big|_{t=0} = t_0\left(x, y\right) \tag{22}$$

Where, h is the comprehensive heat transfer coefficient, [$Wm^{-2}K^{-1}$]. T_f is the ambient temperature, K.

3. Study on phase change heat transfer law of crude oil

3.1. Simulation conditions and independence verification

An indoor test bench was set up for phase-change heat transfer of waxy crude oil during the shutdown, and verification of the phase-change heat transfer model and solution method of crude oil was carried out [18]. In this study, the model was directly used to study the phase change heat transfer of crude oil in the oil tank. The simulated crude oil initial temperature was 50℃, the ambient temperature was -20℃, and the comprehensive heat transfer coefficient between the surface and the environment was 24.8 [$Wm^{-2}K^{-1}$]. The physical parameters of the simulated materials were shown in Table 1. The crude oil freezing point was 32℃, the coalescating point was 37℃, the wax precipitation point was 42℃ and the viscosity was as follow.

$$\mu = 10^{5.06039-0.01951T} \tag{23}$$

Tab.1 Physical parameters of simulated materials

Name/Unit	Density (kg/m^3)	Specific heat capacity (J /(kg·K))	Coefficient of thermal conductivity (W/(m·K))
Crude oil	$\rho = 902 - 0.8177 \cdot (T - 273.15) + 0.00154 \cdot (T - 273.15)^2$	$c_p = \begin{cases} 2401 & T \geq 315.15K \\ -40.84T + 15271 & 292.5K \leq T < 315.15K \\ 16.84T - 1600 & 273.15K \leq T < 292.5K \end{cases}$	Liquid zone crude oil:0.25 Solid zone crude oil:0.15
Steel	7850	500	48
Heat preservation material	60	700	0.04

The grids used were 5860, 22464 and 49323, respectively. The average temperature change curve of crude oil in the oil tank was monitored during simulation, and the results are shown in Fig.2. When the number of grids was 5860, the simulation results had apparent deviation compared with other grids. However, when the number of grids was 22464 and 49323, respectively, the average temperature drop curve of crude oil was basically the same. Therefore, it could be considered that the accuracy was high enough when the number of grids was 22464, so the number of grids would be 22464 when the crude oil tank was simulated in this study.

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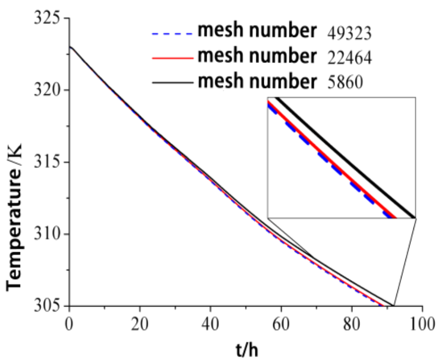


Fig. 2 Average temperature drop curve of crude oil under different grid numbers

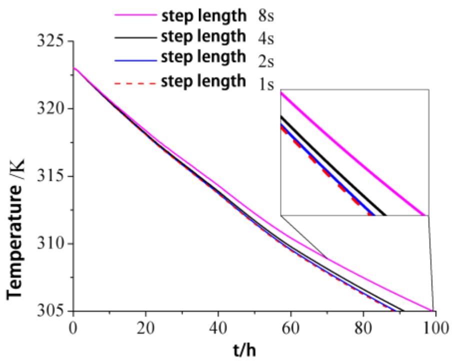
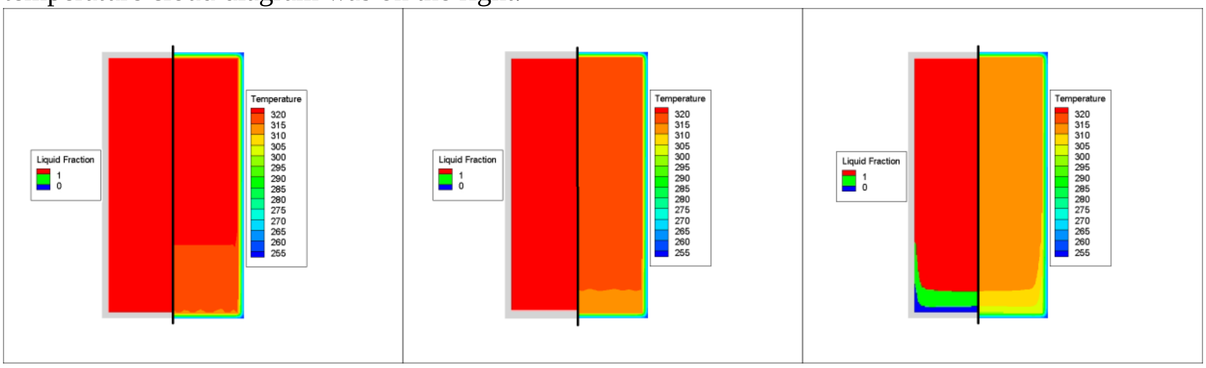


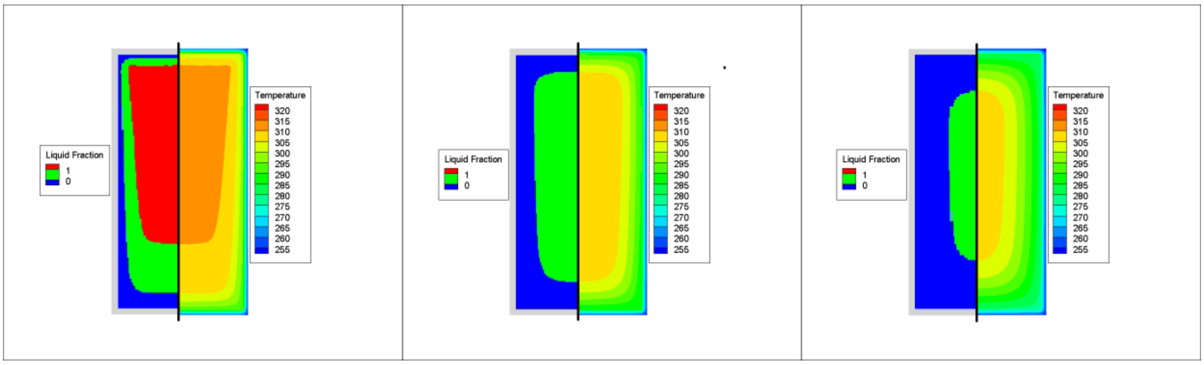
Fig. 3 Average temperature drop curve of crude oil under different time steps

3.2. Variation characteristics of crude oil temperature field and condensate layer

The distribution cloud diagram of the solidification and temperature field at different typical moments in the oil tank was shown in Fig. 4. The solidification cloud diagram was on the left, and the temperature cloud diagram was on the right.



(a) 10 h (b) 20 h (c) 50 h



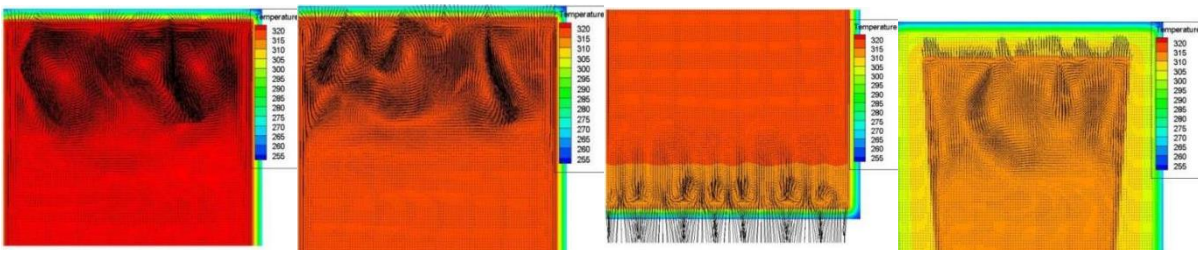
(d) 70 h (e) 100 h (f) 150 h

Fig. 4 Distribution cloud of crude oil temperature field in oil tank at different time

As can be seen from Fig. 4, when the temperature drop time of crude oil was less than 10 h, the temperature of crude oil in the tank was higher than the wax precipitation point, and no wax crystal was precipitated. High-temperature crude oil floated up and concentrated in the ample space at the upper part of the pipeline, and the temperature field was in a state of high and low temperature. When the temperature drop time was 20 h, the oil layer at the bottom of the tank started to precipitate wax crystals, but the oil temperature at the bottom was higher than 310 K, and there was no porous medium. When the temperature drop time increased to 50 h, the oil at the bottom of the tank showed condensate oil and porous medium oil. At 70 h, the high-temperature crude oil was distributed in the middle and upper part of the oil tank in an inverted trapezoidal shape, and the thickness of the porous medium area and condensate oil further increased. With the increase of time to 100 h, there was no liquid oil in the tank, and it became a porous medium entirely. Until 150 h, there was still a tiny amount of crude oil in the porous medium area in the centre of the tank, and the rest of the crude oil had become solidified. At this time, the temperature was almost entirely symmetric in the field and under the field, and the difference caused by convection had disappeared.

3.3. Variation characteristics of crude oil flow field

According to the characteristics of the change of crude oil flow field, the distribution diagram of the flow field at the top and bottom of the oil tank at different times was selected and listed, as shown in Fig. 5 (the black line was the flow field, and the long and dense line indicated that the intensity of the flow field at the position was more vigorous; Otherwise, the intensity of the flow field was weaker).



(a) 10 h, The top of an oil tank (b) 20 h, The top of an oil tank (c) 20 h, The bottom of an oil tank (d) 70 h, The top of an oil tank

Fig. 5 Flow fields at different locations at typical times

There was a density difference of crude oil in oil tanks due to different temperatures at various points, and a gravity field generated the floating force, and natural convection would occur in liquid crude oil. The flow field in the oil tank was mainly concentrated at the top and bottom, as shown in Fig. 5 (a) and Fig. 5 (c). The eddy of the flow field at the top of the oil tank was large, and the cold oil near the pipe wall was transported to the bottom of the oil tank, and the hot oil in the middle of the oil tank was sent to the upper part of the pipeline. By comparing the flow field at 10 h and 20 h, the intensity of the vortex at the top of the oil tank gradually decreased with the decrease in temperature. The flow field at the bottom of the tank was a series of small horizontal vortices. These small vortices transport the cold oil sunk from the side wall of the tank upward, but the strength of the vortices was low, and most of the cold oil was eventually mixed in the lower wall of the tank, resulting in the lowest temperature of the bottom coil of the tank.

Fig.5 (d) showed that the orange part of the Figure was the high-temperature liquid oil, and the dark yellow outer layer was the oil in the porous medium. It could be found that the flow field was mainly concentrated on the interface near the porous medium and the upper part of the liquid oil. As the heat transfer mode of porous media was skeleton heat conduction and convective heat transfer of liquid oil in pores, the heat transfer intensity was much lower than that of convective heat transfer in the liquid oil region, and the flow field lines in the Figure were almost invisible. The liquid oil near the porous medium area permeated with the cold oil in the porous medium area. The cold oil seeped into the liquid oil area and flowed down with the flow field to the bottom of the liquid oil area.

3.4. Variation characteristics of oil layer thickness in different phase zones

Taking the central axis of the oil tank as the standard, the thickness changes of the condensate layer at the top and bottom and the oil layer with porous medium characteristics were shown in Fig. 6.

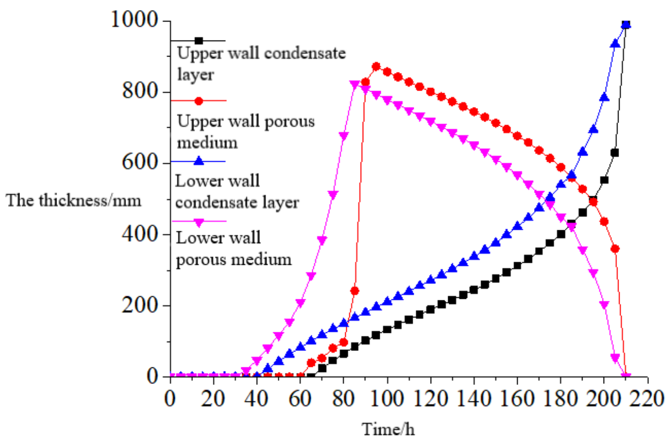


Fig. 6 Thickness changes of condensate layer and porous media at the central axis

From the Fig.6, it can be seen that the thickness of the condensate layer increased exponentially in both the upper and lower walls, and the thickness of the condensate layer on the lower wall of the oil tank was always more significant than that on the upper wall. However, the thickness of the condensate layer on the upper wall of the tank increased rapidly in the later period, and eventually, the two were equal, and the crude oil in the tank completely solidified. Due to buoyancy, hot oil tended to be concentrated in the upper part of the tank, while cold oil tended to be concentrated in the lower part.

The crude oil at the bottom of the tank was more excellent, so the bottom condensate layer appeared earlier. The oil layer with porous medium characteristics showed an exponential growth trend before it reached the maximum thickness and an exponential decrease trend after it reached the maximum thickness. Moreover, because the lower wall oil temperature was lower, the reservoir with porous medium characteristics appeared earlier. In the early stage, the thickness of the lower wall with porous media was more significant than that of the upper wall, which was consistent with the trend of the condensate layer. When the time reached 90 h, the thickness of the oil layer with porous medium property near the upper wall began to exceed that of the lower wall. In the process of heat transfer, the condensate layer on the outside of the upper wall was thicker, with a better insulation effect, and the hot oil tended to gather upward. These reasons led to the slow heat dissipation and long retention time of the oil layer with porous medium characteristics near the upper wall, and it took much work to turn it into condensate oil. So, during the conversion to condensate in the latter half of the curve, the porous medium near the upper wall was thicker than the lower wall.

4. Conclusions

1. The three-phase zonal heat transfer model of waxy crude oil takes into account Newtonian characteristics of crude oil, the nonlinear release of latent heat and the influence of convective heat transfer and accurately describes the phase changes of crude oil in the tank.

2. The main factor affecting the temperature drop rate of crude oil in the oil tank was the heat transfer mode of crude oil. The heat transfer efficiency in the porous medium area was much lower than that in the liquid oil area.

3. Due to the vortex flow field caused by natural convection in the oil tank, the oil temperature distribution presented a state of high and low, leading to the oil condensate layer at the bottom of the oil temperature drop process being thicker.

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