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Numerical study on the temperature drop characteristics of waxy crude oil in a double-plate floating roof oil tank

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ABSTRACT

Physical and mathematical models for the temperature drop process of the waxy crude oil in a double-plate floating roof oil tank are established with the consideration of non-Newtonian behavior and wax precipitation accompanying the phase change of waxy crude oil. Accordingly, an integrative numerical procedure is developed for the calculation. In this study, non-Newtonian behavior is described by power-law equation. Wax precipitation is described by the enthalpy-porous media theory, in which the gel oil interface is tracked. The computer code is validated by the results in literatures. Based on the verified computer code, characteristics of temperature drop in the tank are studied and the influences of wax precipitation amount and non-Newtonian behavior on the temperature drop process are analyzed in detail. The results show that when oil is not gelled, the oil tank can be divided into two parts: (1) the top and middle part of approximate uniform temperature; (2) the bottom part of stratified distribution of temperature. It is also found that increasing of the wax precipitation amount will slow down the temperature drop process and extend the duration of the temporal stable period. Furthermore, when oil temperature is between abnormal point and thixotropy appearance point, whether considering the non-Newtonian behavior or not covers certain influence on temperature drop process, and different non-Newtonian behaviors play less effect. When oil temperature is below thixotropy appearance point, strengthening of the non-Newtonian behavior will slow down the temperature drop process slightly.

1. Introduction

Most of the crude oil produced in China is waxy crude oil which has remarkable features, such as high pour point, high viscosity and complex rheological property. In the production practice, heating treatment is always necessary for the waxy crude oil. Double-plate floating roof oil tank is the most critical oil storage facility, in which waxy crude oil is always stored. During the storage process, temperature of oil gradually drops due to its heat transfer to the atmosphere. When oil temperature is below the wax precipitation point, wax crystals start to precipitate in the liquid oil. When wax precipitation amount reaches 1–2% [1,2] or 2–3% [3] of the whole oil mass, the oil would gelatinize, which seriously affects the production practice and may even cause accidents. Thus, it is of great necessity to study the temperature drop process of waxy crude oil in the double-plate floating roof oil tank and obtain a better understanding of the temperature drop characteristics of the oil. This contributes to a better arrangement of the storage time and a more reasonable plan of turnover operation.

There are mainly two approaches to study the flow and heat transfer process in the oil tank: experimental study [4,5] and numerical study [6–15], between which numerical simulation has been preferred in recent years due to its low cost, short research period and comprehensive research results. In the area of numerical simulation, due to the complex of waxy crude oil composition and the double-plate floating roof oil tank structure and the strong turbulent flow and heat transfer in the tank, which results in large amount of calculation. Therefore, former researchers studied the oil temperature drop process in a small size model tank based on some assumptions [6–14]. Oliveski [6] studied the cooling process of the high Pr number fluid in tanks of different sizes using finite volume method. Correlations between Nu number versus ratio of height to radius, dimensionless total heat

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Nomenclature

g_s	wax precipitation amount	n	flow behavior index
ΔH	latent heat in the mushy region, J/kg	T	temperature, °C
K	consistency coefficient, Pa s^n	u	waxy crude oil velocity, m/s
K_d	permeability of wax crystal porous media, m^2	u_s	wax crystal velocity, m/s
K_0	permeability constant, m^2		
L	latent heat, J/kg		

transfer coefficient, Ra and Pr numbers were obtained. Papanicolaou [7] studied the unsteady-state natural convection with different Ra numbers in the 2D cylindrical-symmetric region which was similar with the oil tank, by four different low-Reynolds number k-ε models. Lin [8] adopted laminar flow model and scaling analysis methods to perform numerical simulation for the long-time cooling process of Newtonian fluid with $1 \leq \mathrm{Pr} \leq 1000$, $6 \times 10^6 \leq \mathrm{Ra} \leq 6 \times 10^{10}$. Correlations between fluid temperature and temperature drop time versus Ra were also obtained by fitting. Based on the axial symmetry of the oil tank, Li [15] simplified the three dimensional 100,000 m^3 double-plate floating roof oil tank to a two dimensional one, and studied the temperature drop process in the tank with the consideration of the air layer at the tank top, insulating layer at the tank wall and soil layer under the tank. Influences from floating deck type, insulating layer thickness, liquid height, oil property and wind velocity were analyzed. It was found that influences from floating deck type, insulating layer thickness and liquid height were much greater than the influences from oil property and wind velocity.

Although some studies have been performed for the flow and heat transfer characteristics of waxy crude oil (fluid with high Pr number) in the tank, non-Newtonian behavior and wax precipitation were not considered in these studies. Actually, these two factors may exert great influences on the temperature drop process of waxy crude oil. Based on this, this paper proposes a temperature drop model incorporating non-Newtonian behavior and wax precipitation. Numerical methods are employed to study the temperature drop characteristics in a double-plate floating roof oil tank and the influences from wax precipitation amount and non-Newtonian behavior on the temperature drop process are analyzed in detail.

2. Physical and mathematical models

2.1. Physical model

Double-plate floating roof oil tank consists of: air layer and steel plate layer at the tank top, steel layer and soil layer at tank bottom, steel layer and insulating layer at tank wall as well as the waxy crude oil in the tank. Thus, heat transfer in a double-plate floating roof oil tank involves gas-solid (air layer and steel layer), liquid-solid (waxy crude oil and steel layer) and solid-solid (steel layer and insulating layer or steel layer and soil) coupled heat transfer and force convection between tank body and atmosphere.

On the other hand, the state and rheological behavior of waxy crude oil will be changed during the temperature drop process. At the initial moment, the oil temperature is higher than the wax precipitation point T_w, and the waxy crude oil appears as pure liquid and shows Newtonian behavior. When oil temperature drops below the wax precipitation point, wax crystals begin to precipitate and the solid-liquid dispersion system begins to form. At this moment, the waxy crude oil still shows Newtonian behavior. When oil temperature is below the abnormal point T_a, it begins to show non-Newtonian characteristics. At this stage, the solid-liquid dispersion system still exists. When oil temperature is below thixotropy appearance point T_t, wax crystals in the oil begin to link with each other and form wax crystal porous media, which will exert binding effect on the oil [3]. Table 1 shows the changes of the waxy crude oil state and rheological behavior during the temperature drop process.

Furthermore, due to the large size of actual tank and the violent turbulent process (For a commonly used 100,000 m^3 double-plate floating roof oil tank, it radius and height are 40 m and 20 m respectively. When temperature difference between the oil and environment is 30 °C, the Ra number is reaches up to 7.0×10^{15}), the calculation amount and calculating time are unacceptable. Besides, the aim of this research is to establish a physical and mathematical models of the temperature drop process in a double-plate floating roof oil tank with the consideration of non-Newtonian behavior and wax precipitation and then study the temperature drop characteristics in the tank. Considering the axial symmetry of the oil tank, the three-dimensional double-plate floating roof oil tank is simplified into a two-dimensional one, as shown in Fig. 1. It's worth pointing out that steel layer at the tank wall is not considered in this model because of its much larger heat conductivity compared to the insulating layer, which leads to a very small inner temperature gradient and little impact on the temperature drop process in the tank.

2.2. Mathematical model

Mathematical model is established in the two-dimensional cylindrical coordinate system. Eqs. (1)-(4) show the governing equations involving the non-Newtonian behavior [16–21] and wax precipitation [22–29] of waxy crude oil, where natural convection is described by the Boussinesq approximation.

Considering the gas-liquid-solid coupled heat transfer process involved in this paper, solid (steel layer and insulating layer) is considered as fluid of infinite viscosity, in order to realize an integration solving. Besides, the Ra number in the tank is 6.0×10^{12}, laminar model is used [7]. Governing equations contain: mass conservation equation, momentum equation and energy conservation equation, as Eqs. (1)-(4) show.

$$\frac{\partial(\rho u_x)}{\partial x} + \frac{1}{r}\frac{\partial(r\rho u_r)}{\partial r} = 0 \tag{1}$$

$$\frac{\partial(\rho u_x)}{\partial t} + \frac{\partial(\rho u_x u_x)}{\partial x} + \frac{1}{r}\frac{\partial(r\rho u_r u_x)}{\partial r} = \frac{\partial}{\partial x}\left(\mu\frac{\partial u_x}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial u_x}{\partial r}\right) - \frac{\partial p}{\partial x} + \rho g\beta(T - T_c) + s_{ux} \tag{2}$$

$$\frac{\partial(\rho u_r)}{\partial t} + \frac{\partial(\rho u_x u_r)}{\partial x} + \frac{1}{r}\frac{\partial(r\rho u_r u_r)}{\partial r} = \frac{\partial}{\partial x}\left(\mu\frac{\partial u_r}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial u_r}{\partial r}\right) - \frac{\partial p}{\partial r} - \frac{\mu u_r}{r^2} + s_{ur} \tag{3}$$

$$\frac{\partial(\rho c_p T)}{\partial t} + \frac{\partial(\rho c_p u_x T)}{\partial x} + \frac{1}{r}\frac{\partial(r\rho c_p u_r T)}{\partial r} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda\frac{\partial T}{\partial r}\right) + s_h \tag{4}$$