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Research Paper

Experimental and numerical study on the heat transfer characteristics of waxy crude oil in a 100,000 m^3 double-plate floating roof oil tank

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HIGHLIGHTS

- Experimental and numerical studies are performed to investigate the heat transfer characteristics in the tank.
- Variations of the rheological behavior and phase change are considered in the model.
- Evolutions of the flow and heat transfer in the tank are studied in detail.
- Variations of the heat flux on tank top, bottom and wall are analyzed.

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ABSTRACT

100,000 m^3 double-plate floating roof oil tank is the most widely used tank for waxy crude oil storage in petroleum industry. A detailed study on the heat transfer characteristics of waxy crude oil in the tank is of great significance for storage safety, tank structure optimization and energy conservation. In this paper, experimental and numerical approaches are jointly adopted to study the heat transfer characteristics in the tank for a long-term storage. On the aspect of experimental investigation, thermal sensors are installed in the tank to monitor the oil temperature and obtain the temperature drop curve and vertical temperature distribution. On the aspect of numerical investigation, with the consideration of non-Newtonian behavior and phase change (wax precipitation or melt), physical and mathematical models for the heat transfer characteristics of waxy crude oil in a double-plate floating roof oil tank are established. Taking a 100,000 m^3 double-plate floating roof oil tank as example, the evolution of temperature, turbulent kinetic energy and turbulent viscosity is studied, and the variations of the heat flux on tank top, tank bottom and tank wall are analyzed in detail.

1. Introduction

Almost all of the crude oil produced in China is waxy crude oil. Waxy crude oil has the characteristics of high pour point, high viscosity and complicated rheological behavior, therefore it needs to be heated during storage. Double-plate floating roof oil tank is the most commonly used vessel for waxy crude oil storage [1]. During its storage, heat continuously transfers from oil to the environment and oil temperature drops accordingly. When oil temperature drops to below wax precipitation point, wax crystals start to precipitate. When the wax precipitation amount reaches 1–2% [2,3] or 2–3% [4] of the total mass of oil, the oil starts to gel, which seriously threatens the safety of storage vessel and waxy crude oil storage process. On the other hand, according to the report, the amount of the waxy crude oil reserved in China reaches up to 33.25 million tons by the middle of 2016. Therefore, an accurate understanding on the heat transfer characteristics of different kinds of waxy crude oil in different areas of China in a double-plate floating roof oil tank is of crucial importance on the scientific designing of the oil tank structure, optimization of oil tank operation schedule and improving energy efficiency.

There are generally two research approaches on the heat transfer process of waxy crude oil during storage: experimental study [5–8] and numerical study [9–15]. It is noteworthy to indicate that due to the complexity of the waxy crude oil produced in China, Chinese researchers make more efforts on this subject. Rao et al. [5] invented an equipment of oil temperature measurement and applied it on the

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temperature field measuring of 100,000 m^3 double-plate floating roof oil tank. In the measurement, 115 measuring points are installed, whose locations are allocated on the surface layer, shallow layer, deep layer and bottom layer of oil. A long-term oil temperature field was successfully obtained within this study. Yu et al. [6] divided the oil tank into surface layer, shallow layer and deep layer, and allocated thermal sensors in these layers. Sensors are also set on the shade part and subsurface area. Measuring points showed that temperature drop process of oil can be divided into three stages: rapid drop stage, condensate oil layer increasing stage and integral slow drop stage. To study the oil temperature drop process in particular cases, some model tanks were constructed. Satisfying the law of similarity, temperature measuring results in the model tanks were used to study the oil temperature drop characteristics in the actual oil tank [7]. Pasley et al. [7] designed a model tank with diameter of 6.1 m and height of 2.35 m. With this tank, influences from wind on the oil temperature field within the cases of empty, 1/2 load and 3/4 load were experimentally studied. Though experimental study is an important approach to reveal the characteristics of oil temperature drop in the tank, it is limited on the following aspects: (1) experimental results are highly influenced by the tank structure, oil property and weather condition, etc., which limits the application of the experimental results; (2) although lots of thermal sensors are installed in the tank, only limited information can be obtained and much important information is inevitably neglected. Due to these limitations, numerical approach has increasingly shows its advantages in recent years.

Lin et al. [9] adopted numerical approach to study the oil temperature drop characteristics in a tank with height-diameter ratio of 1/3–1, *Pr* number of 1–1000 and *Ra* number of $6 \times 10^6 \sim 6 \times 10^{10}$. Based on the numerical results, correlations between dimensionless temperature with time, height-diameter ratio, *Pr* number and *Ra* number are obtained by scale analysis. Oliveski et al. [10] applied both experimental and numerical approaches to study the temperature and velocity fields of oil in an experimental tank with *Ra* number of 4.3×10^9 and 3.1×10^9 for 15 h storage. In this study, velocity vector near the top area and the tank wall area were studied, and the oil temperature distribution along the vertical central line of the tank was analyzed. Finite volume method is adopted to study the oil temperature drop process in the experimental tanks of various volumes [11]. Correlations between Nu number versus dimensionless height-diameter ratio, dimensionless total heat transfer coefficient, *Ra* number and *Pr* number were fitted with dimensional method. Zhao et al. [12] performed a simulation for the waxy crude oil gelatinization process in a 10,000 m^3 double-plate floating roof oil tank for 80 days storage on the basis of laminar model. Evolution of the oil gelatinization process and increasing of the gel oil thickness on the tank wall were analyzed. Besides, influences from atmosphere temperature on the oil gelatinization in the tank were studied.

From the above analyze, it can be seen that numerical study is also limited in the following aspects: (1) most of them were conducted on the small size tank, and few researches has been conducted on the most widely used 100,000 m^3 double-plate floating roof tank; (2) oil was always simplified to Newtonian fluid; (3) phase change (wax precipitation or melt) of oil during storage was not considered; (4) the storage time is relatively short (several hours or days). Overcoming these shortages, the heat transfer characteristics in a 100,000 m^3 double-plate floating roof oil tank during long-term storage are studied, in which experimental and numerical approaches are jointly adopted in this research. The evolution of temperature and turbulent kinetic energy and turbulent viscosity of oil are studied in detail, and the variations of the heat flux on tank top, tank bottom and tank wall are also analyzed in detail.

2. Experimental investigation

In experiments, thermal sensors are installed in a 100,000 m^3 double-plate floating roof oil tank situated in northwestern China. The arrangement of the thermal sensors is shown in Table 1 and Fig. 1.

Table 1
Thermal sensors arrangement in the oil tank.

Monitoring point	Location	Arrangement
Point 1 and point 7	0.5 m from tank wall	The distance from monitoring point
Point 2 and point 6	2.0 m from tank wall	to tank bottom: 1.0 m, 4.0 m, 7.0 m,
Point 3 and point 5	10.0 m from tank wall	10.0 m, 13.0 m and 16.0 m
Point 4	Central axis of the tank	(refinement on tank top and bottom)

3. Numerical investigation

3.1. Physical model

Heat transfer system of a double-plate floating roof oil tank can be divided into two parts: oil tank and adjacent soil. The oil tank can be further subdivided into: air layer, steel layer, insulating layer and waxy crude oil. Heat transfer system in a double-plate floating roof tank consists of: (1) gas-liquid-solid coupled heat transfer within the tank; (2) heat conduction between oil tank and adjacent soil; (3) forced convection between oil tank and atmosphere; (4) solar radiation.

During the storage, oil state and rheological behavior keep changing. At the beginning, oil temperature is relatively high and the oil exists as pure liquid and shows Newtonian behavior. When oil temperature drops to wax precipitation point T_w, wax crystals begin to precipitate and solid-liquid dispersion system begins to form. At this stage, oil still behaves as Newtonian fluid. When oil temperature drops to abnormal point T_a, oil begins to show non-Newtonian behavior. At this stage, oil still exists as solid-liquid dispersion system. When oil temperature continuously drops to thixotropy appearance point T_t, the precipitated wax crystals begin to connect with each other and form the waxy crystal porous media [4]. Table 2 shows the variations of the oil state and rheological behavior.

For a 100,000 m^3 double-plate floating roof oil tank, whose radius is 40 m, when the temperature difference is 30 °C, the *Ra* number can reach up to 6.0×10^{15}. In this situation, for a 3D simulation on the tank, the computation amount and computation time are unacceptable. Therefore, considering the axisymmetry of the tank, the 3D tank is simplified into a 2D one in the simulation, as Fig. 2 shows.

3.2. Mathematical model

With the consideration of non-Newtonian behavior [16–18] and phase change (wax precipitation or melt) [19–23] of waxy crude oil in the tank, the mathematical model is described in this section. Considering that the heat transfer process in the tank involves of gas-liquid-solid coupling, to accelerate the calculation process, the solid parts of the oil tank (steel layer and insulating layer) are considered as liquid with infinite viscosity while other parameters keep unchanged. With this treatment, the heat transfer of gas-liquid-solid coupling process is transferred into a variant thermo-physical properties process. In this way, an integrated solution approach is realized. Further, the standard *k*-*ε* model is adopted in this paper to calculate the turbulent flow and heat transfer process in the tank. In a 2D cylindrical coordinate system, the governing equations can be written as:

(a) Continuity equation

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