Thermal Analysis of Crude Oil in Floating Roof Tank Equipped with Horizontal Heating Finned Tube Bundles

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Abstract

Keeping crude oil within the working temperature range in a floating roof tank is the key to ensuring the safe operation of the oil depot. Tubular heating is one of the conventional and extensive methods to heat crude oil. To improve the flow and heat transfer performance of crude oil during the heating process, comprehensive numerical research is presented to investigate heat transfer and flow characteristics of crude oil in which the heating tube is arranged with and without fins, and the impact of fin length and fin number on temperature field, flow field and heat flux of crude oil was investigated. The results show that by increasing fin length, the average temperature of crude oil increases and inhomogeneity in temperature decreases. The most homogeneous temperature distribution is attained by the tube with a 200 mm length fin where the maximum amplitude is 1.9 °C. The improvement of heating performance with 4 fins is significant from the aspect of temperature distribution and temperature rise of crude oil. Moreover, the amount of heat flux at the tank wall decreases with increasing fin length and fin number, and the maximum decrease is 4.39 % for the tube equipped with a 150 mm length fin, while other tank boundaries do not have an apparent changing rule.

Keywords: Floating roof tank; Fin; Heating tube bundles; Heat transfer and flow performance; Heating process.

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1. Introduction

Energy is an important material foundation and economic driving force for social development.^[1,2] Strategic petroleum reserve is one of the key indicators to evaluate national energy security.^[3,4] With the increasing demand for strategic crude oil reserves in China, floating roof tanks are the preferred storage equipment for large-scale crude oil depots due to their technical and economic advantages.^[5-8] However, most of the crude oil produced in China is waxy crude oil, which has the characteristics of high viscosity and complex rheology.^[9,10] There is a risk of gelatinization of waxy crude oil during the static storage period when suffers from an extremely low ambient temperature. In general, heating is one of the most appropriate strategies to avoid risk and enhance the safety of crude oil storage.^[11] Plenty of methods have been developed to heat crude oil, such as local heating technology^[12] and full heating technology.^[13]

Among these, tubular heating is one of the traditional and extensive methods for full heating technology where heating tubes are usually placed at the bottom of a floating roof tank near the tank wall in order to promote crude oil heating performance by natural convection induced by the change of crude oil density. The heat transfer and flow performance in the natural convection of crude oil during the heating process are important for designing the heating tube in a floating roof tank, and there are two main research methods for heat transfer and flow performance of crude oil in floating roof tank,^[14,15] including experimental measurement and numerical simulation. Zhao *et al.*^[16] experimentally investigated the temperature profile in a 10 × 10⁴ cubic meter double-deck floating roof tank, and analyzed the effects of test position and ambient temperature on temperature distribution. Yu *et al.*^[17] experimentally analyzed the process of temperature drop of crude oil by installing a temperature measurement system in a floating roof tank, and indicated that the crude oil stored in a floating roof tank has three processes, which include overall rapid temperature drop stage, condensate growth stage, and overall heat conduction cooling stage. Considering the difficulty of full-scale engineering experiments, researchers have adopted small-scale experimental methods to investigate the temperature field of crude oil based on similarity theory or

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dimensional analysis. Pasley *et al.*^[14] designed a model tank with a diameter of 6.1 m and height of 2.35 m, and conducted an experimental study on oil temperature distribution under empty, 1/2 loaded, and 3/4 loaded crude oil stock in a floating-roof oil storage tank. Mawire *et al.*^[18] used an electric heating plate as a heat source to test the heat transfer performance of oil, and found that the heat transfer performance of oil improves linearly with the increment of electric power. Besides, Rejane *et al.*^[19] experimentally investigated the heat transfer and flow performance of crude oil in a floating roof tank.

Besides experimental measurement, there are numerical simulation methods to investigate the impact of natural convection on the thermal performance of crude oil as the heat transfer and flow of crude oil are coupled.^[20-27] Rejane *et al.*^[28] numerically studied the heat transfer characteristics of a small-volume storage tank using the finite volume method (FVM), and obtained the temperature field of crude oil in a vertical storage tank. Sun *et al.*^[29,30] established a theoretical model of the coil heating process in a floating roof tank to investigate the effect of coil structure on the coupling features of heat transfer and flow of crude oil, and evaluated the heating effect of crude oil as well as energy efficiency. In the same way, some researchers^[31-35] also numerically investigated the heat transfer and flow of crude oil in a floating roof tank.

Although the above-mentioned researches are helpful to understand heat transfer and flow performance of crude oil in floating roof tank, most of them focus on the analysis of crude oil temperature field under static storage, and the enhanced heat transfer mechanism of tubular heating has not been elucidated in detail, especially in the aspect of optimizing heating tube structure, such as the application of fins by extending heat transfer surface area between crude oil and heating tube. To the best of the authors' knowledge, the research on heat transfer and flow coupling in the heating process of crude oil by means of a heating tube with fin is limited. Therefore, the present work is devoted to investigating the heat transfer and flow performance of crude oil by heating tubes with and without fins during the heating process. The impacts of fin length and fin number on the temperature field, flow field, and heat flux of crude oil were investigated. The findings of this research are hoped to be helpful for enhancing heating effectiveness and optimizing the structure of the heating tube.

2. Physical and mathematical models

2.1 Geometric description

In general, a floating roof tank is composed of the bottom, lateral and top walls, and accessories, among which the accessories mainly include a rotating escalator, drainage pipe, vent valve, measuring tube, heating tube, ring wall, reinforcing ring, sealing device, *etc.* The walls of the tank (*i.e.* bottom, top, and lateral walls) are made of steel plate. There are two types of floating roof tanks: single-plate floating roof tanks and double-plate floating roof tanks, both of which are

not equipped with thermally insulating material on the top wall. However, the lateral tank wall is covered with an insulating layer to reduce heat exchange between the tank wall and the surrounding environment. A photo of a floating roof tank in the Daqing oilfield of China is presented in Fig. 1.

Fig. 1 A photo of a floating roof tank.

To simplify the analysis, the sketch of a floating roof tank with a heating tube is illustrated in Fig. 2. Since the system of the floating roof tank is axisymmetric, the computational domain for the heat transfer and flow analysis is simplified to a two-dimensional axisymmetric model. Considering the effect of soil on the heat transfer process of crude oil, the heat-influenced region (it is considered that there is the interaction between the floating roof tank and soil layer at the bottom wall of the tank in the thermally affected area, and soil layer is almost no longer affected by floating roof tank after thermal influence area is exceeded) of floating roof tank was given based on the similar concept of thermal pipelines,^[36,37] *i.e.* a constant temperature layer of soil away from the bottom wall in the depth of H_2 and an insulation boundary away from the lateral wall in the distance of L_3 were considered.^[10,32] The top and lateral walls of the tank, and soil exposed to the environment are modeled considering coupled heat transfer of heat convection and solar radiation.

Fig. 2 The sketch of a floating roof tank with the heating tube.

Four different configurations of heating tube regarding the fin are considered: i) tube without a fin, ii) tube with 2 fins (straight-shaped), iii) tube with 4 fins (cross-shaped), and iv) tube with 6 fins (snow-shaped). The schematic diagram of the heating tube with fins is shown in Fig. 3.

Fig. 3 The schematic diagram of the heating tube with various fin shapes a) no fin, b) straight-shaped fin, c) cross-shaped fin, and d) snow-shaped fin.

2.2 Governing equations and boundary conditions

To analyze the complex nature of transient flow and conjugate heat transfer involving thermal conduction, natural convection, and solar radiation, some assumptions are made as listed below:

- (1) The Boussinesq approximation is adopted for the buoyancy of crude oil,^[9] and the viscous dissipation term is ignored.
- (2) Crude oil and soil are isotropic media, and the thermophysical properties of crude oil depend on temperature, as well as the viscosity of crude oil can be described approximately by the power-law equation.^[31]
- (3) Due to the low proportion of total heat transfer of wax in crude oil, the latent heat of wax is omitted.^[31]
- (4) Since heating finned tube bundles are made of steel which has high thermal conductivity, the surface temperature of heating finned tube bundles is treated as constant.

Based on the above assumptions, the governing equations for the heat transfer and flow process of crude oil are presented as follows.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0$$

x-momentum equation:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left((\mu + \mu_t) \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left((\mu + \mu_t) \frac{\partial u}{\partial y} \right) \quad (2)$$

y-momentum equation:

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left((\mu + \mu_t) \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left((\mu + \mu_t) \frac{\partial v}{\partial y} \right) + \rho g \beta (T - T_m) \quad (3)$$

Energy equation:

$$\frac{\partial(\rho c T)}{\partial t} + \frac{\partial(\rho c u T)}{\partial x} + \frac{\partial(\rho c v T)}{\partial y} = \frac{\partial}{\partial x} \left(\left(\lambda + \frac{c \mu_t}{Pr_t} \right) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\left(\lambda + \frac{c \mu_t}{Pr_t} \right) \frac{\partial T}{\partial y} \right) \quad (4)$$

where t is the time (s). ρ , c , λ and β stand for the density (kg/m^3), specific heat ($\text{J/(kg}\cdot\text{K)}$), thermal conductivity

($\text{W/(m}\cdot\text{K)}$), and thermal expansion coefficient ($1/\text{K}$) of crude oil, respectively. p and g represent the pressure (Pa) and gravitational acceleration (m/s^2), respectively. μ and ν are velocities in x and y directions. μ_t and Pr_t are respectively the turbulent viscosity coefficient and turbulent Prandtl number. T and T_m stand for the temperature (K) and reference temperature (K), respectively.

The thermophysical properties of crude oil including density, specific heat,^[32] thermal conductivity,^[31] and dynamic viscosity^[31] all of which are temperature-dependent are obtained by the following expressions:

$$\rho = \rho_{ref} (1 - \beta(T - T_{ref})) \quad (5)$$

$$\lambda = 0.1568 - 7.378 \times 10^{-7} T \quad (6)$$

$$\mu = \begin{cases} -29558 + 3905.2T - 171.13T^2 + 3.2339T^3 - 0.0224T^4 & (T \leq 44^\circ\text{C}) \\ 2113.1 + 4.833T & (T > 44^\circ\text{C}) \end{cases} \quad (7)$$

$$\mu = e^{-28.8+8904.4/(273.15+T)} \quad (8)$$

The boundary conditions can be described as follows:

For the top of the tank (i.e. $0 \leq x \leq L_1$, $y = H_1 + H_2$):

$$-\lambda \frac{\partial T}{\partial y} = h_{top}(T_{top} - T_{zt}) \quad (9)$$

For the lateral wall of the tank (i.e. $x = L_1$, $H_1 \leq y \leq H_1 + H_2$):

$$-\lambda \frac{\partial T}{\partial x} = h_{wall}(T_{wall} - T_{zw}) \quad (10)$$

For $L_1 \leq x \leq L_1 + L_3$, $y = H_2$:

$$-\lambda \frac{\partial T}{\partial y} = h_{soil}(T_{soil} - T_{zs}) \quad (11)$$

For $x = 0$, $0 \leq y \leq H_1 + H_2$:

$$\frac{\partial T}{\partial x} = 0 \quad (12)$$

For $x = L_2$, $0 \leq y \leq H_2$:

$$\frac{\partial T}{\partial x} = 0 \quad (13)$$

(1) For the soil bottom (i.e. $0 \leq x \leq L_2$, $y = 0$):

$$T = T_{soil} \quad (14)$$

For the heating tube:

$$T = T_{heating tube} \quad (15)$$

where T_{zt} , T_{zw} , and T_{zs} stand for respectively the solar-air temperature (K) of the top, lateral wall, and bottom of the tank, and are defined as^[38-41]

$$T_{zt} = T_{zw} = T_{zs} = T_{air} + \frac{I}{h} \quad (16)$$

Here, T_{air} is the ambient temperature (K), I is the solar radiation intensity (W/m^2), and h is the heat convection coefficient ($\text{W/(m}^2\cdot\text{K)}$), which can be predicted as follows:^[9]

$$h = 11.63 + 7.0\sqrt{V} \quad (17)$$

where V is the average wind velocity (m/s).

2.3 Method of solution and validation of numerical procedure

Heat transfer and flow simulations are carried out by the commercial software ANSYS Fluent, and the large eddy simulation (LES) method is adopted to solve the turbulent flow of crude oil.^[9,42,43] The second-order upwind scheme which avoids numerical diffusion is implemented to discretize the advective terms in the energy equation. Pressure and velocity fields are coupled by the SIMPLE algorithm while the interpolation of pressure is handled by the Body Force Weighted scheme and second-order implicit transient approximation is implemented. The convergence residual values are set to be less than 10^{-3} , 10^{-3} , and 10^{-6} for continuity, momentum, and energy equations, respectively.

Fig. 4 Validation of numerical model with the experimental data of Ref. [31].

Verification of the established numerical model with experimental work which also considers the varying thermophysical properties of crude oil and solar radiation is essential to confirm the accuracy and reliability of the model. Fig. 4 shows the comparison between simulation and experimental results in the literature.^[31] The simulated and

measured data are in good agreement, in which the maximum relative error and average relative error are 7.5% and 3.9%.

In order to determine an appropriate mesh and time step size, a series of tests are conducted for three different meshes of 122,857, 204,173, and 478,740 elements and time step sizes of 10 s, 20 s, and 50 s. Since the present work involves a number of cases including the heating tube with various fins, the simulations are carried out for a heating tube having 4 fins with a length of 200 mm, hence the mesh independent test can be assured for the other considered cases also. In addition, a non-uniform structured mesh is generated for the discretization of the computational domain, and the mesh near solid surfaces (i.e. near the top, bottom, lateral walls of tank and heating tubes) is dense due to the large gradients of temperature and velocity whereas relatively coarse meshes are adopted in the rest of the domain. The mesh test presented in Fig. 5 has exhibited that the mesh with 204,173 elements can sufficiently ensure mesh-independent results for the problem under consideration. Regarding the results of these series of tests and computation time, the time step size of 20 s is employed for further computations.

3. Results and discussion

In a present research study, in order to evaluate the impacts of fin length and fin number on heat transfer and flow performance of crude oil during the heating period, three parameters are selected: i) oil zone average temperature, which is an indicator of temperature enhanced of crude oil, ii) surface heat flux of floating roof tank boundary which is related to the heat losses toward surrounding (including ambient and soil) and iii) the inhomogeneity of temperature field which reflects the index of temperature distribution of crude oil in floating roof tank,^[29] and presents the degree of temperature distribution between points in the space. The smaller value of this index exhibits better uniformity in the oil zone temperature field. The expression of temperature inhomogeneity is given as:

Fig. 5 Validation of mesh number and time step size.

$$\Delta T = \sqrt{\frac{1}{5}[(T_c - T_a)^2 + (T_t - T_a)^2 + (T_{wr} - T_a)^2 + (T_{wl} - T_a)^2 + (T_b - T_a)^2]} \quad (18)$$

where ΔT is the temperature inhomogeneity (K). T_c is the central temperature (K), T_t , T_{wr} , T_{wl} , and T_b are the average temperature (K) of the top, right side wall, left side, and bottom walls of the floating roof tank, respectively, and T_a is the oil zone average temperature (K).

The ambient temperature and average wind velocity are 20 °C and 6 m/s. The solar radiation intensity is 770 W/m². The reference density of crude oil is 860 kg/m³ at a reference temperature of 20 °C, and the thermal expansion coefficient is 0.00062 1/K.^[31] The heating tube position is 2 m away from the lateral wall (*i.e.* w , in Fig. 2) and 0.5 m away from the bottom (*i.e.* h , in Fig. 2), as well as all heating tube spacing is 0.5 m. The number and diameter of the heating tube are 5, and 0.05 m, respectively. The thickness of the insulation layer, steel layer, and fin are 0.06 m, 0.01 m, and 0.002 m. The surface temperature of heating tube bundles and soil bottom is 80 °C and 10 °C, and the initial temperature of the oil zone and soil zone are 35 °C and 30 °C, respectively. The thermophysical properties of materials^[30,32] are given in Table 1.

Table 1. The thermophysical properties of materials.^[30,32]

Materials	Thermal conductivity (W/(m·K))	Specific heat (J/(kg·K))	Density (kg/m ³)
Steel	40	460	7800
Soil	1.74	1750	1600
Insulating material	0.035	800	60

Numerical simulations are performed for different combinations of heating tubes considering fin length and fin number. The simulation scheme of heat transfer and flow performance of crude oil in a floating roof tank equipped with heating finned tube bundles is presented in Table 2.

Table 2. Simulation scheme of heat transfer and flow performance of crude oil in floating roof tank equipped with horizontal heating finned tube bundles.

Case	Heating tube bundle number	Fin length (mm)	Fin number
1	5	-	0
2	5	100	4
3	5	150	4
4	5	200	4
5	5	100	2
6	5	100	6

3.1 Effects of fin length

In this section, heat transfer and flow performances of crude oil with various fin lengths (0, 100, 150, and 200 mm) were investigated, and the fin number is fixed to 4, *i.e.* the analysis

is done for the cross-shaped fin. A heating tube without a fin is regarded as a comparison basis.

Figure 6 shows the temperature and velocity contours of the oil zone with different fin lengths. Evidently, the improvement of the oil zone temperature and the heating area is better than that of the heating tube without a fin. Increasing fin length can effectively enhance heat transfer performance. When the heating time is 1 day, it can be seen that a thermal plume is formed near the lateral wall of the tank and the thermal plume wakes to appear near the top wall of the tank. The reason for this phenomenon is that the density of heated oil decreases with natural convection driven. With increasing the heating time, the temperature of the top wall becomes higher compared to other domains due to the impact of solar radiation, thus temperature stratification gradually occurs for the region far away from the tank wall. Referring to the velocity contours of crude oil in Fig. 6, it can be observed that the velocity fields of crude oil with fins are more intense and the affected regions are larger than that of the case without fins. This behavior is aggravated by increasing in length. On the other hand, as time goes on, the velocity of crude oil gradually decreases due to the increase in crude oil temperature and the whole crude oil temperature tends to be the same. As a quantitative example, the average velocities of crude oil are 3.94×10^{-5} m/s, 1.64×10^{-5} m/s for the finless tube and 7.5×10^{-5} m/s, 2.85×10^{-5} m/s for the heating tube with 200 mm fin on the first day and 20th day of heating, respectively.

Figure 7 illustrates the average temperature curves of crude oil zone with different fin lengths. As seen in Fig. 7, increasing fin length has a significant effect on the average temperature within 20 days. Compared with the tube without fin, the average temperature increases by 0.9, 1.47, and 1.9 °C for the fin lengths of 100, 150, and 200 mm, respectively. On the other hand, with the increment of fin length, the reinforcement effect of oil temperature shows a declining trend. As the fin length is progressively increased from 0 to 100, 100 to 150 and then 150 to 200 mm, the enhancement rates are 2.49, 1.51, and 1.17 % at each aforementioned step of fin length increment. The results indicate that the degree of oil temperature strengthening decreases when the fin lengths are too long, thus an optimal length should be chosen according to its thermal performance, and manufacturing and investment costs.

Figure 8 shows the temperature inhomogeneity at various times for different fin lengths. Evidently, the trends of temperature inhomogeneity basically increase at first and then decrease, and reach a peak on the second day, its value ranges between 5.4°C-5.6°C. It is also seen that the temperature inhomogeneity of crude oil heated by the tube with fin is lower than that of the tube without fin, and the temperature inhomogeneity of a heating tube with a 200 mm fin length is the lowest. Within the whole heating period, the average

Fig. 6 Temperature and velocity contours of oil zone with different fin lengths.

Fig. 7 Average temperature of oil zone for different fin lengths within the heating period.

temperature inhomogeneity is 5.59 °C for the tube without fin, 5.42 °C for the tube+fin (100 mm), 5.35 °C for the tube+fin (150 mm), and 5.3 °C for the tube+fin (200 mm). Compared with the bare tube (*i.e.* the tube without fin), the temperature inhomogeneity is reduced by 3.04% for the tube+fin (100mm), 4.29 % for the tube+fin (150 mm), 5.19 % for the tube+fin (200 mm). Combined with Fig. 7, it can be concluded that the highest oil zone temperature is attained by the heating tube with a 200 mm length fin where the temperature distribution is the most uniform.

Figure 9 shows the total surface heat flux at the top, side wall, and bottom of the floating roof tank. As seen in the figure, the trend of heat flux gradually reduces, and the ranges of heat flux at the top and bottom of the tank are larger, varying from 0 to 70 W/m² at the top and from 0 to 50 W/m² at the bottom,

while it is between 4 and 7 W/m² at the tank wall. The reason for this enormous deviation of the heat flux is the large temperature difference between the top and bottom of the tank and the surrounding environment in the initial period, and as time elapses, the heat exchange continues between the tank boundary layer and surrounding environment until the heat transfer stabilizes gradually. On the tank wall, the variation of heat flux is weak due to the existence of an insulation layer. On the other hand, with incrementing the fin length, the total surface heat flux at the bottom of the floating roof tank increases, while the total surface heat flux at other boundaries has no obvious regularity. The results indicate that the layout of the heating tube has a certain influence on the heat transfer through the floating roof tank boundary. In other words, the t closer the heating tube is to the floating roof tank boundary, the greater the heat loss.

Fig. 8 Temperature inhomogeneity with different fin lengths within the heating period.

Fig. 9 Total surface heat flux of tank boundary with different fin lengths a) at the top, b) at the bottom, and c) at the lateral wall of the tank where q_i and q_0 are the total surface heat fluxes of the tank boundary equipped with heating tube bundles with and without a fin, respectively.

In order to quantify the heat flux at each tank boundary intuitively, Fig. 10 presents a histogram of the total surface heat flux of each tank wall in the entire heating period. As seen in the figure, the total surface heat fluxes are 44–48 kW/m² at the top wall, 38–40 kW/m² at the lateral wall, and 16–18 kW/m² at the bottom wall, respectively. Moreover, the total heat flux of the tank wall equipped with fins is slightly lower compared with the bare tube where the reduction is 1.28 % for the tube+fin (100 mm), 4.39 % for the tube+fin (150 mm), and 3.87 % for the tube+fin (200 mm). It can be seen from Fig. 10 that the heat flux on the top, lateral and bottom walls account for 44–45 %, 37–38 %, and 16–17 %, respectively. Namely, comparing the total heat fluxes from the tank boundary, they

are in decreasing order of the top wall, lateral wall, and bottom wall. Therefore, from the point of view of energy saving, the present work will be beneficial to future research on structure insulation of floating roof tanks.

3.2 Effects of fin number

In this section, heat transfer and flow performance of crude oil with different fin numbers (0, 2, 4, and 6) was examined, where the fin length is kept constant at 100 mm, *i.e.* the analyses are done for the straight-shaped fin, cross-shaped fin, and snow-shaped fin, respectively. A heating tube without a fin is regarded as a comparison basis.

Fig. 10 The proportion of the heat flux from different walls of the tank to total heat flux during the whole heating period (20 days).

Fig.11 Temperature contours of crude oil and heating tube area with different fin numbers at various times.

Figure 11 shows the temperature contours of crude oil with different fin numbers at various times. Similarly, the impact of fin number on the temperature distribution of crude oil is alike to that of fin length. It can be observed that the heated area gradually increases with time. In addition, although increasing the fin number can improve oil zone temperature, the heating effect is not as obvious as increasing fin length, and the temperature rise near the tank wall is also not that strong. In order to clearly show the temperature distribution near the heating tube area, Fig. 11 compared the temperature contours of crude oil heated by the bare tube and the tube with 6 fins in the region of the heating tube. It can be seen that the temperatures of crude oil near the heating tube are higher than that of another crude oil zone, and the high-temperature range of crude oil near the tube with 6 fins is larger than that of the unfinned tube due to the expansion of heating tube area.

Figure 12 shows the velocity vectors of crude oil with different fin numbers at various times. Likewise, the influences of fin number on the flow field of crude oil are similar to that of fin length. In the initial and end periods of the heating process, the average velocities of the whole crude oil zone are respectively 3.94×10^{-5} m/s and 1.64×10^{-5} m/s for the tube without fin, and 5.89×10^{-5} m/s and 2.52×10^{-5} m/s for the tube with 6 fins. On the other hand, in the vicinity of the heater zone, the average velocities of crude oil in the initial and end periods of the heating process are 7.77×10^{-5} m/s and 5.82×10^{-5} m/s for the tube without a fin, and 6.61×10^{-5} m/s and 5.59×10^{-5} m/s for the tube with 6 fins, respectively. The reason for this result is the crude oil average temperature in the vicinity of the heater zone is higher and more even distribution when the existence of fins and crude oil density difference near the heater zone is smaller, as

Fig.12 Velocity vectors of crude oil for the heating tube with different fin numbers.

well as the natural convection is weaker, therefore the average velocities of crude oil with fins are smaller than that of without fins. Meanwhile, the results further demonstrate that increasing the fin number can improve the whole crude oil velocity due to the larger temperature difference between the fluid near the heater and another crude oil zone by extending the heat exchange area.

Figure 13 shows the average temperature of the crude oil zone with different fin numbers. As shown in Fig. 13, an increasing number of fins has a significant effect on the average temperature of the oil zone during the heating period. Compared with the heating tube without a fin, the oil zone average temperature increases by 0.73, 0.9, and 0.67 °C for the tube with 2, 4, and 6 fins, respectively. On the other hand, with the increase of fin number, the reinforcement effect of oil temperature shows a declining trend or even decreases. For example, the enhancement rate is 2.02 % when the tube with 2 fins is utilized instead of the bare tube (*i.e.* unfinned tube), and 0.46 % when the fin number is increased from 2 to 4. However, when the fin number is further increased, meaning that 6 fins on the tube, there is a decrement of 0.62 % compared to the tube with 4 fins. The results show that increasing the fin number is not always beneficial for the rise of crude oil temperature, and there is an optimal fin number for the suitable thermal regulation of crude oil during the heating process, and the present work can provide a reference for future researches on optimizing the fin number.

Fig. 13 Average temperature of oil zone for different fin numbers within the heating period.

Figure 14 shows the temperature inhomogeneity of crude oil fields with different fin numbers within the heating period. As obviously seen from the figure, the trends of temperature inhomogeneity first increase and then decrease, and they reach a peak on the second day where the value is in the range of 5.4 °C- 5.7 °C. On the other hand, the temperature inhomogeneity of the crude oil field heated by the tube with fin is lower than that of the unfinned tube, and the temperature inhomogeneity of the tube with 4 fins is the lowest. Within the whole heating

period, the average temperature inhomogeneity is 5.59 °C for the tube without fin, 5.46 °C for the tube + 2 fins, 5.42 °C for the tube+4 fins, and 5.48 °C for the tube + 6 fins, respectively. Compared with the unfinned tube, the temperature inhomogeneity reduces by 2.33, 3.04, and 1.97 %, respectively. Regarding the above-presented results and those in Fig. 13, it can be concluded that the heating tube with 4 fins provides the highest enhancement in the oil zone temperature and a more uniform temperature distribution.

Fig. 14 Temperature inhomogeneity for different fin numbers within the heating period.

Figure 15 shows the sum of the total surface heat flux at the top, lateral wall, and bottom of the floating roof tank. As seen in the figure, the trend of heat flux gradually reduces with increasing time, and the range of heat flux is larger at the top (varying from 0 to 65 W/m²) and at the bottom (varying from 0 to 45 W/m²), while it varies between 4 to 7 W/m² on the lateral wall of the tank. In addition, the total surface heat flux at the bottom of the floating roof tank increases with increasing fin number, while the total surface heat flux at other walls does not follow a specific changing rule.

Similarly, for a better understanding of the heat flux at each tank boundary intuitively, Fig. 16 presents the histogram of the total surface heat flux of each tank boundary over the entire heating period. As seen in the figure, the total surface heat flux varies between 46-47 kW/m² for the top, 37-38 kW/m² for the lateral wall, and 16-18 kW/m² for the bottom of the tank. Compared with the unfinned tube, the total heat flux of the tank wall reduces slightly when fins are attached to the tube where the reduction is 1.62 % for tube + 2 fins, 1.27 % for tube + 4 fins, and 0.87 % for tube + 6 fins. Referring to Table 3, the heat flux from the top wall, lateral wall, and bottom wall of the tank accounts for 44 % - 45 %, 37 - 38 %, and 16 % - 17 % of the overall heat flux from the tank, respectively, which means that top wall > lateral wall > bottom wall in terms of the magnitude of heat flux.

Fig. 15 Variation of total surface heat flux from the tank with different fin numbers over time a) at the top, b) at the bottom, and c) at the lateral wall of the tank (q_i and q_0 are the total surface heat flux of tank wall equipped with heating tube bundles with and without fin).

Fig. 16 Total surface heat flux of floating roof tank in the whole heating period (20 days).

Table 3. Approximate proportion of total surface heat flux of floating roof tank in the whole heating period (20 days).

	Top wall	Lateral wall	Bottom wall
A portion of surface heat flux to total heat flux	44%-45%	37%-38%	16%-17%

4. Conclusions

In this study, the heat transfer and flow performance of crude oil in a floating roof tank during the heating process was investigated in terms of temperature field, flow field, and heat flux of crude oil. The effect of fin attachment to the heating tube was explored by considering various fin lengths (0, 100 mm, 150 mm, and 200 mm), and fin numbers (0, 2, 4, and 6). The main conclusions can be drawn as follows:

- Fins play an essential role in the heat transfer and flow performance of crude oil during the heating period. Increasing fin length, the maximum average temperature and temperature homogeneity of the oil zone improve by 1.9 °C, and 5.19 % for 200 mm in length, compared to the heating tube without fin. Nevertheless, the enhancement effect is insignificant beyond the fin length of 150 mm.
- The improvement of oil zone temperature by fin number is more significant than that of fin length. Compared with the heating tube without a fin, the temperature inhomogeneity in the entire oil zone reduces when fins are added. On the whole, the reduction in the temperature inhomogeneity is similar for all fin numbers, where the average magnitude is 5.42 °C (cut down by about 3 %) for the heating tube with 4 fins.
- By increasing fin length and fin number, the intensity of natural convection and velocity of the whole crude oil zone increases obviously, while the crude oil velocity near the heating tube is low due to the decrease in the temperature and density gradient of crude oil.

Increasing fin length and fin number have an insignificant impact on the heat flux of tank walls. The relationship between the amount of heat flux at each tank wall is in order of top wall>lateral wall>bottom wall, corresponding to the proportion of 44 % - 45 %, 37 - 38 %, and 16 % - 17 %, respectively.

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Supporting information

Not Applicable

Conflict of interest

There are no conflicts to declare.

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