Effect of Periodic Change of Ambient Temperature on the Temperature Field in the Single Disc Floating Roof Oil Tank

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Abstract

In this paper, it is more practical to use periodic ambient temperature in the simulation of cooling. Additional specific heat capacity and momentum source terms methods are employed to simulate the changing physical properties of waxy crude oil related to the paraffin crystallization. The changes of temperature field of tanks especially for heat dissipation and the cooling rate of top wall and sidewall were compared with 6 m and 8 m diameter under three different periodic temperatures. Our outcomes reveal that the heat dissipation and the temperature drop rate at the top wall and sidewall fluctuated in accordance with the periodic change of ambient temperature. For storage tanks of different sizes, the heat dissipation of large tanks is larger especially on the top wall, but smaller tanks have a faster rate of temperature drop especially on the sidewall. Meanwhile, the average ambient temperature affects the overall size of heat dissipation and temperature drop rate, the lower the average ambient temperature is, the higher the temperature drop rate and heat dissipation will be. And the fluctuation of ambient temperature affects the fluctuation rule of heat dissipation and temperature drop rate, the larger the fluctuation of ambient temperature, the larger the fluctuation of heat dissipation and temperature drop rate.

Key Words: Waxy Crude Oil, Periodic Ambient Temperature, Cooling Rate, Heat Dissipation

1. Introduction

Waxy crude oil accounts for a large proportion of national crude oil reserves and production in China. At present, China’s total crude oil reserves have exceeded 70 million tons [1] and the annual output exceeds 100 million tons [2]. Due to the technical and economic advantages of large floating roof storage tank, it has become the preferred equipment for large crude oil storage under the increasing demand for oil storage [3]. During the static storage of crude oil, the paraffin in the waxy crude oil gradually precipitate and form a network structure which is called gelatinization structure. The gelatinization structure formed at the top wall, sidewall and base wall will affect the economical and safe storage of tank. Therefore, in order to ensure the safety and economic operation of the storage tank, it is necessary to accurately grasp the temperature field under the changed of ambient temperature.

Based on the practical engineering significance, some scholars have done considerable research on it. Sun [4,5] simulated the influence of solar radiation and periodic change of ambient temperature on the internal temperature field of $10 \times 10^4$ m$^3$ floating roof storage tank in Daqing through numerical simulation and qualitatively analyzed the influence of boundary conditions on the temperature field inside the tank. However, only a few scholars have studied periodic boundary conditions due to the difficulty of simulating. And more scholars take the boundary conditions as quantitative analysis to ana-
alyze the changes of temperature field in the cooling process. Li [6,7] investigated the thermal characteristics of crude oil during its storage, and the effects of solar radiation and thickness of insulating layer on the thermal performance of crude oil tank were discussed. Zhao [8,9] analyzed the radial temperature distribution of different liquid levels in the crude oil tank based on the finite volume method. Shao [10] obtained the influence of the diameter and liquid level of storage tanks on the temperature distribution by simulating the temperature distribution changes of storage tanks with different volumes during the standing process. Wang [11–14] mainly analyzed the phase transition of waxy crude oil during cooling process and studied the non-newtonian behavior of waxy crude oil under low temperature and low shear rate. Zhao [15–18] quantitatively obtained the influence of physical properties of crude oil on heat transfer characteristics by analyzing the evolution of temperature field, velocity field and gelling structure of waxy crude oil. Zhang [19] and Rong [20] simulated the cooling process of the storage tank and studied the gelling process of waxy crude oil by imitating Zhao's method. Yang [21] designed a temperature test system for the floating roof oil tank, and carried out the temperature test for the cooling process of a 100,000 m³ double-plate floating roof oil tank in Daqing oil field. Based on the test data, the temperature distribution in the tank under different environment temperature and operating states were investigated. The temperature and velocity distribution of crude oil nearby tank wall in double-deck floating roof tank is studied by Liu [22]. According to the heat dissipation of storage tanks with different ambient temperatures, some scholars have carried out relevant researches. Mawire A [23, 24] conducted the experiment and simulated the thermal process of a small un-insulated oil storage tank subjected to heat losses during charging. The characteristics of thermal gradients in the tank and the influence factors were evaluated in detailed. After that, based on the experimental method, Mawire A [25] investigated the de-stratification and heat loss characteristics of three oils in a small storage tank during 24 h low temperature and medium temperature cool down cycles. And the temperature, stratification number and heat loss factor profiles was studied under different conditions. Darzi [26] analyzed the effect of ambient temperature change on the oil in the tank through experiments. Ren [27,28] analyzes the temperature distribution law of gas-liquid phase for oil storage tanks with gas phase. At the same time, the response process of pressure in the tank, oil temperature and the temperature of the wall were analyzed based on the test and the influence of the temperature of the wall on temperature field and velocity field was studied.

The above research provides a basic method to study the temperature drop of crude oil during static storage. Based on the analysis of the above references, the existing researches mainly have the following problems: (1) Most scholars set the boundary temperature as a constant temperature when studying the temperature drop in the storage tank, but the periodic change of the ambient temperature with time has a significant impact on the temperature drop; (2) A few scholars considered the influence of periodic change of ambient temperature of the storage tank in the research process, and there are few researches on the influence of different ambient temperature on temperature field in different tanks. The main purpose of this study is to analyze the evolution of temperature field of oil in the tank under the influence of periodic change of ambient temperature. Under the effect of periodic change of ambient temperature, the simulation results will be more realistic. Based on the knowledge of the temperature distribution and its evolution of waxy crude oil, the locations of temperature monitoring points can be more reasonably designed, which is of great significance to guide the operation and management of oil tank.

2. Physical Models

So as to illustrate the establishment process of the computational domain, the simplified process of the storage tank is presented in Figure 1.

In order to ensure the safe storage of waxy crude oil, its temperature is usually heated to higher than the surroundings. The heat is transferred from the oil in the tank to the surroundings through the top wall and sidewall of the tank by the temperature difference. The actual structure of single deck floating roof tank is very complex, except for the floating roof, sidewall and base wall, there are lots of accessories such as the roof supports, guide pole, wind girder, inlet and outlet, et al. The axisym-
metric model of thermodynamic system is obtained if some simplifications and assumptions are introduced [15,17,19,20,29].

3. Mathematical Model, Numerical Approach and Verification Process

3.1 Mathematical Model

The momentum source terms is used to represent the additional flow resistance caused by the yield characteristic of waxy crude oil. As this flow resistance enhances with the temperature drops, the parameter \( C \) in the momentum source term is used to establish the relationship with the temperature. And parameter \( C \) is taken as a constant which is used to compromise the flow resistance and the momentum source term. It is believed that when the flow resistance caused by the yield characteristic surpasses the buoyancy force from convection, the waxy crude oil begins to gelatinize. At this moment, the value of parameter \( C \) is taken as 0, and based on the equivalent relationship between the buoyancy force and flow resistance, the calculated value of parameter \( C \) is determined.

The integrated governing equations for the heat transfer process of waxy crude oil are shown as follows.

3.1.1 Flow and Heat Transfer Equation

For the two-dimensional axisymmetric storage tank model established, the basic governing equation can be described as:

(1) Flow heat transfer equation

Equation of Continuity:

\[
\frac{\partial \rho_u}{\partial t} + \frac{\partial (\rho u u)}{\partial x} + \frac{1}{r} \frac{\partial (\rho u v)}{\partial r} = 0
\]  

Momentum Equation:

\[
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u u)}{\partial x} + \frac{1}{r} \frac{\partial (\rho u v)}{\partial r} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \mu \frac{\partial u}{\partial x} \right) \\
+ \frac{1}{r} \frac{\partial}{\partial r} \left( \mu \frac{\partial u}{\partial r} \right) - \rho g + S_u
\]  

\[
\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho u v)}{\partial x} + \frac{1}{r} \frac{\partial (\rho v v)}{\partial r} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( \mu \frac{\partial v}{\partial x} \right) \\
+ \frac{1}{r} \frac{\partial}{\partial r} \left( \mu \frac{\partial v}{\partial r} \right) - \frac{\mu v}{r^2} + S_v
\]

where,

\[
S_u = \frac{(1-\beta)^2}{(\beta^3 + 0.001)} \cdot C \cdot u
\]  

\[
S_v = \frac{(1-\beta)^2}{(\beta^3 + 0.001)} \cdot C \cdot v
\]

\[ T_0 > T_z \quad \beta = 1 \]  

\[ T_0 < T_z \quad \beta = 0 \]  

\[ T_z < T_0 < T_i \quad \beta = \frac{T_i - T_z}{T_i - T_z} \]  

\( T_i \) is losing flow temperature of crude oil and \( T_z \) is gelting temperature of crude oil.

Energy Equation:

\[
\frac{\partial (\rho C_p T)}{\partial t} + \frac{\partial (\rho C_p u T)}{\partial x} + \frac{1}{r} \frac{\partial (\rho C_p v T)}{\partial r} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda \frac{\partial T}{\partial r} \right)
\]
Differential equation of heat conduction for solid structure:
\[
\frac{\partial(\rho T)}{\partial t} = \frac{k}{C_p} \left[ \frac{\partial^2 T}{\partial x^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \right]
\]

(10)

### 3.1.2 Boundary conditions

External surface of the single deck:
\[
x = H_{\text{tank}}, \quad -R_{\text{tank}} \leq r \leq 0, \quad -\lambda_{\text{soil}} \frac{\partial T_{\text{soil}}}{\partial x} = h_{\text{soil}} (f(T) - T_{\text{soil}})
\]

(11)

Other walls which contact with air are also set as the third boundary condition.

Thermal influence boundary:
\[
r = -R_{\text{soil}}, \quad -H_{\text{soil}} \leq x \leq 0, \quad q_{r,x} = 0
\]

(12)

Constant temperature layer:
\[
x = -R_{\text{soil}}, \quad -R_{\text{soil}} \leq r \leq 0, \quad T_{r,x} = T'
\]

(13)

Axis of symmetry:
\[
r = 0, \quad H_{\text{tank}} \leq x \leq -H_{\text{soil}}, \quad -k \frac{\partial T}{\partial r} = 0
\]

(14)

### 3.1.3 Initial condition

In the initial stage of simulation, the internal temperature of crude oil remains constant and uniform. Since there is no temperature difference at this time, there is no flow of internal crude oil, and the velocity in the axial and radial directions are 0.

\[
T_c (r, x) = T_0, \quad u_0 (r, x) = v_0 (r, x) = 0
\]

(15)

### 3.2 Numerical Approach

In this paper, finite volume method is used to solve the governing equation and boundary conditions. Taking into consideration of the structure of the computational domain, the structured quadrilateral grids are adopted. Since the temperature gradient at the top wall, sidewall and base wall are the largest, the grid is encrypted in this area. In the radial direction, the nearest grid distance is 9.9 mm from the tank wall, and expands 80 grids to 216 mm at a rate of 1%, and 1200 mm from the tank wall, and then grows to 684 mm at a rate of 0.5%. In the axial direction, the nearest grid distance from the top wall and base wall of the tank is 259 mm respectively, and expands 100 grids to the center of the tank at the same expansion rate of 0.5%. At this time, the width of the grid is 424 mm. The number of grids in the radial waxy crude oil calculation area are 330, the number of grids in the axial waxy crude oil calculation area are 200, the total number of quadrilateral grids in the oil product calculation area are 66000, and the number of grids in the whole calculation area are 125495. The detailed design scheme of the calculation area is shown in Figure 2.

### 3.3 Discretization of the Control Equation

Based on the designed mesh system, the computational region is discretized into large amount of meshes. For each mesh, the discretization of the control equations can be accomplished based on the finite volume method. Specifically, for the discretization of the transient term, the fully implicit first order temporal differentiation is used. The diffusive terms have been evaluated using a second order central differences scheme, while convective terms have been approximated by means of the high order QUICK scheme. The Body Force Weighted scheme has been used for the discretization of pressure in consideration of the existence of buoyancy force caused by convection. Furthermore, the coupling between pressure and velocity fields has been solved by the PISO algorithm with additional correction to improve the efficiency of pressure-velocity coupling calculation. The algebraic system of equations resulting for each variable has been solved by using a multigrid method.

### 3.4 Validation Process

#### 3.4.1 Validation of the Mesh System

In order to verify the applicability of the grid system designed in this paper, several grid systems are compared. In the simulation process, the top wall was set to constant temperature, the sidewall and base wall of the tank were set to adiabatic, and the two groups were set to compare working conditions. Grid 1, Grid 2 and Grid 3 are named for the meshes which the nearest grid distance from the top wall was 5 mm, 9.9 mm and 15 mm respectively. The calculation results of different grids were compared. The initial oil temperature was 40°C and the tank top temperature was 10°C for numerical simula-
tion. The calculation results of the top wall Nu number based on different grid systems were shown in Figure 3. According to the data in Figure 3, the Nu on the top wall of Grid 2 and Grid 1 are not different from each other. The Nu of Grid 1 and Grid 2 maintain the same trend and have higher similarity during the cooling process, the error is smaller compared with Grid 3. Therefore, in order to improve computing efficiency, it is appropriate to adopt a grid system with a minimum grid width of 9.9 mm at the tank top.

3.4.2 Validation of the Numerical Approaches

There is a $2 \times 10^3$ m$^3$ single deck floating roof storage tank in a certain area of Daqing. The temperature test device is used to record the time-varying temperature at 2 m away from the base wall and 2 m away from the side-wall. The actual test results are compared with the numerical simulation results. The results show that the error between the numerical simulation results and the test results is within the allowable range of engineering.

4. Results and Discussion

4.1 Simulation Cases

By simulating the tank model that the height of the storage tank is 6.8 m and the radius is 11 m. The diameter of the thermal-affected region is 12.5 m, thermal influence boundary is adiabatic boundary and heat flux is 0. The temperature of the constant temperature layer is 5 °C, for other surfaces in contact with the ambient environment. The periodic ambient temperature $f(T)$ is:

$$f(T) = \begin{cases} 
-18.5 + 5.5\sin\left(\frac{\pi}{12} \times t - 1.57\right), & 0 \leq t < 24 \\
-21.5 + 4.5\sin\left(\frac{\pi}{12} \times t - 1.57\right), & 24 \leq t < 48 \\
-19.5 + 5.5\sin\left(\frac{\pi}{12} \times t - 1.57\right), & 48 \leq t < 72 \\
-19 + 5\sin\left(\frac{\pi}{12} \times t - 1.57\right), & 72 \leq t < 96 \\
-19.5 + 5.5\sin\left(\frac{\pi}{12} \times t - 1.57\right), & 96 \leq t < 120 \\
-22 + 6\sin\left(\frac{\pi}{12} \times t - 1.57\right), & 120 \leq t < 144 \\
-24.5 + 5.5\sin\left(\frac{\pi}{12} \times t - 1.57\right), & 144 \leq t < 168 \\
-26.5 + 5.5\sin\left(\frac{\pi}{12} \times t - 1.57\right), & 168 \leq t < 192 \\
-28 + 5\sin\left(\frac{\pi}{12} \times t - 1.57\right), & 192 \leq t < 216 \\
-29 + 5.5\sin\left(\frac{\pi}{12} \times t - 1.57\right), & 216 \leq t < 220 
\end{cases}$$

The temperature assumed in this paper is set by re-
ferring to the winter temperature of Daqing. The minimum temperature in Daqing can reach -35 °C in winter, and the average temperature can reach -22 °C. As the ambient temperature reaches the lowest value in winter, the influence of periodic change of ambient temperature on the temperature field of crude oil can be judged better.

Rheology behaviors of waxy crude oil is very complicated. When the temperature is higher than the losing flow point, its viscosity is related to the temperature of waxy crude oil. When the temperature is lower than the losing flow point, the viscosity is affected by temperature and shear rate. However, because the variation of shear rate changes very little due to cooling, the viscosity data at different temperatures measured from the low shear rate experiment are used in the simulation as Figure 4(a). The latent heat caused by the paraffin crystallization is represented by additional specific heat capacity. Taking into consideration of the latent heat induced by the paraffin crystallization, the specific heat of waxy crude oil at different temperatures is shown as Figure 4(b). In the range of 24 °C–44 °C, the specific heat capacity increases gradually with the decrease of temperature. It is the release of latent heat during paraffin crystallization that leads to the increase of specific heat capacity.

The data of viscosity is measured by therheometer (Anton paar QC). The latent heat caused by the paraffin crystallization is represented by additional specific heat capacity. The data of specific heat capacity as a function of temperature is measured by DSC following the method (TA Q2000). The yield characteristic of waxy crude oil is represented by the sink term in the momentum equation which changes with temperature. The losing flow point temperature is 34 °C, while the jelled point temperature is 30 °C for the waxy crude oil. The density of crude oil is assumed as a constant except in the buoyance terms of the momentum equations (Boussinesq approximation). It is 850 kg/m³ at 20 °C and its coefficient of thermal expansion is 0.000844 K⁻¹. The thermal conductivity is regarded as a constant and the value is 0.14 W/m·K.

4.2 Analysis of the Effect of Periodic Change of Ambient Temperature

In order to explore the influence of periodic change of ambient temperature changes on the temperature field, the heat dissipation at the top wall and sidewall and the cooling rate at different axial and radial positions over time were studied. The influence range of ambient periodic temperature on temperature field is studied.

Figure 4. (a) Viscosity as a function of temperature. (b) Specific heat as a function of temperature.
4.2.1 The Influence of Periodic Change of Ambient Temperature on Heat Dissipation of Storage Tank

Because the heat in the oil area is mostly transferred to the outside through the sidewall and top wall which connect the oil and the ambient environment. The heat dissipation be transferred to the soil through the base wall has little relationship with the periodic change of ambient temperature. So this paper mainly studies the relationship between the heat dissipation from the sidewall and top wall to the periodic change of ambient temperature. The heat dissipation from the top wall and sidewall and the change of ambient temperature over time can be seen in Figure 5.

In Figure 5, the blue curve represents the ambient temperature, corresponding to the left vertical axis; the red curve shows the heat dissipation, corresponding to the right vertical axis. As can be seen in Figure 5(a), with the progress of cooling, the heat dissipation from the oil through the top wall decline gradually, and the falling rate gradually increases in a parabolic shape. As for the relationship between the heat dissipation of oil and the ambient temperature, it can be seen that in the fluctuation of the ambient temperature, the heat dissipation of oil through the top wall also has corresponding fluctuations. When the ambient temperature reaches the peak, the heat dissipation from the top wall reaches the lowest, and when the environmental temperature is the lowest, the heat dissipation from the top wall reaches the peak. This is due to the heat dissipation is related to the temperature difference between the ambient temperature and the temperature near the top wall. The oil temperature is relative to the ambient temperature is much higher and the temperature of the oil relative to the ambient temperature changes more slowly. The increase of the ambient temperature will reduce the difference between the oil and the ambient temperature, and the heat dissipation will decrease gradually. When the ambient temperature reaches the peak correspond to the minimum heat dissipation. This phenomenon is also reflected in Figure 5(b). The gradual decline in the heat dissipation of oil can be understood as the oil near the tank wall and the top of the tank forms the gelling structure with the heat dissipates. Heat conduction have become the main way of heat dissipation, so heat dissipation continues to decline. As for the change of heat dissipation from the top wall and sidewall, it can be seen that heat dissipation from the top wall play a dominant role in the heat dissipation process. The heat dissipation of the top wall of the tank is about 1.4 times that of the sidewall. The heat dissipation is in the range of 75–35 W/m² from the top wall and the heat dissipation from the sidewall is within the range of 55–25 W/m². The top wall is the main area of heat dissipation, and the periodic fluctuation range of heat dissipation caused by the periodic change of ambient temperature on the top wall is also 1.4 times of the sidewall.

4.2.2 The Influence of Periodic Change of Ambient Temperature on the Temperature Distribution of Storage Tank

In the radial direction of the crude oil in the tank, the positions where 0.05 m, 0.1 m, 0.2 m, 0.5 m and 1 m...
away from the sidewall were studied. In the axial direction, the positions where 0.05 m, 0.1 m, 0.2 m, 0.5 m and 1 m away from the tank top were studied. As shown in Figure 6, the function curves of cooling rate of axial and radial positions and ambient temperature with time are presented.

In Figure 6, the cooling rate is indicated by different curves of blue, red, green, cyan and pink, corresponding to the left vertical axis; the solid black curve shows the ambient temperature, corresponding to the right vertical axis. As can be seen in Figure 6(a), the curves of cooling rate at different radial positions and ambient temperature are presented. It can be seen that in the first 36 h, the cooling rate of oil goes down from 0.4 °C/h to about 0.05 °C/h with the cooling. After 36 h, the cooling rate remains stable roughly and maintained at 0.05 °C/h, and fluctuated with the periodic change of the external temperature. In the process of cooling, there are big fluctuations in the cooling rate curve at different radial positions and these fluctuations correspond to the fluctuations of the ambient temperature curve: when the ambient temperature reaches the peak, the radial cooling rate is the lowest, and when the ambient temperature is the lowest, the cooling rate is the fastest. It is because the cooling rate of oil is related to the ambient temperature. The higher the temperature of the ambient temperature is, the slower the heat dissipation rate of crude oil will be, and the lower the rate of heat dissipation will be. For different radial positions, the closer it is to the sidewall, the greater the cooling rate is, and the greater the fluctuation of cooling rate is. The closer it is to the sidewall, the more it is affected by periodic change of ambient temperature.

Figure 6(b) shows the variation curve of cooling rate at different axial positions and the curves of ambient temperature. After 12 h, the cooling rate remains stable roughly and maintained at 0.025 °C/h, and fluctuated with the periodic change of the external temperature. Before 168 h, it showed a consistent change law with the radial direction, that is when the ambient temperature reached the peak, the axial cooling rate was the lowest, and when the ambient temperature was the lowest, the cooling rate was the fastest. However, the process of cooling showed different characteristics after 168 h. The cooling rate rises sharply at the axial position closest to the top wall. It is because the oil started to gel at 168 h at 0.05 m away from the top wall with a sharp decline in fluidity. As can be seen from Figure 6, the main influence area of ambient temperature on oil in the tank is the area near the top wall and sidewall. The effect of periodic ambient temperature on cooling rate is most significant near the top wall and sidewall, especially the sidewall. The cooling rate at 0.05 m from the sidewall is twice as fast as that at the top wall.

4.3 Analysis of the Effect of Periodic Change of Ambient Temperature to Different Tank

In the actual storage tanks, the dimensions are not consistent. The different sizes of storage tanks will be affected inconsistently under the same ambient temperature. Following the establishment process of the above mathematical model and physical model, two new storage tanks were established with the same height and the
radius of 8 m and 6 m respectively. The evolution law of temperature field of storage tanks with different radius under the same periodic change of ambient temperature is studied.

Firstly, the heat dissipation of top wall and sidewall is shown in Figure 7 by comparing the periodic change of ambient temperature as shown in equation 16 with different radius.

In Figure 7, the black curve represents the ambient temperature, corresponding to the right vertical axis; the blue and red curve shows the heat dissipation, corresponding to the left vertical axis. The heat dissipation gradually decreases with the cooling process and presents a fluctuation similar to the periodic change of ambient temperature. The heat dissipation varies with the radius of the tank. As can be seen in Figure 7(a), the heat dissipation at the top of the tank with radius of 8 m was higher than that of the tank with radius of 6 m. The heat dissipation of the tank with a radius of 8 m at the top is $3.5 - 5$ W/m$^2$ larger than that of the tank with a radius of 6 m, and this difference remains relatively stable during the cooling process. As can be seen from Figure 7(b), the heat dissipation at the top wall also shows the same trend, that is, the heat dissipation at the top wall with a large radius is greater. The heat dissipation of the tank with a radius of 8 m on the sidewall is $2 - 4$ W/m$^2$ larger than that of the tank with a radius of 6 m. It indicates that the heat dissipation from the tank increases with the increase of the radius with the cooling process advance. Meanwhile, by comparing Figure 7(a) and (b), it can be seen that the heat dissipation on the top wall dominates in the process of cooling, and the fluctuation range of heat dissipation near the top wall is larger. This indicates that more attention should be paid to the insulation measures of the roof of tank during the cooling process, and the top wall is affected by the periodic change of ambient temperature to a greater extent.

In order to verify the influence of periodic change of ambient temperature on the coupling relationship between oil heat dissipation and temperature field in the tank, the functional relationship between the average temperature at 0.05 m near the top wall and sidewall over time is shown in Figure 8.

In Figure 8, the black curve represents the ambient temperature, corresponding to the right vertical axis; the blue and red curve shows the temperature drop rate, corresponding to the left vertical axis. As can be seen in Figure 8(a), the temperature drop rates of tanks with different radius show similar rules in the first 40 h at the temperature drop at 0.05 m from sidewall. The cold oil sinks under the action of natural convection and the crude oil near the top wall and sidewall maintains a roughly stable temperature drop rate. After the temperature drop of 40 h, the temperature drop rate of tank with radius of 6 m was slightly higher at 0.05 m close to the sidewall after that, the temperature drop rate of the storage tank with a radius of 6 m reaches the maximum temperature drop of $0.98 ^\circ C/h$ at 48 h and the temperature drop rate of the storage tank with a radius of 8 m reached the maximum temperature drop of $0.89 ^\circ C/h$ at 72 h. In each cooling rate period after 72 hours, the maximum temperature drop rate decreases gradually. As can be seen in Figure

**Figure 7.** Evolution of heat dissipation of the tank with different radius.
8(b), similar to the temperature drop rate of 0.05 m from the sidewall, the temperature drop rate of 0.05 m from the top wall with different radius was similar in the first 30 h. After 30 h, the temperature drop rate appears obvious fluctuation corresponding to the periodic change of ambient temperature and the temperature drop rate is slightly larger with the radius of 6 m. The sharp rise in temperature drop rate because of the location is very close to the sidewall and top wall. At this time of crude oil has gelled and the heat transfer by convection heat transfer into thermal conductivity. Corresponding to the temperature drop rate at 0.05 m from the top wall after 168 h as shown in Figure 6(b), the time of gelling structure is earlier as the storage tank is smaller.

It can be seen from Figure 7 and Figure 8 that, in the whole process of cooling, the heat dissipation of tanks with different radius always maintains the same trend. The higher the ambient temperature, the smaller the heat dissipation of the tank. The heat dissipating of tanks with large radius is always higher and the difference of heat dissipating of tanks with different radius is roughly equal. At the same time, it can be seen that the heat dissipation on the top wall is the largest and the fluctuation degree is most affected by the periodic change of ambient temperature. Therefore, the insulation measures on the top wall can effectively reduce the heat dissipation in engineering practice. For the temperature drop rate, it is approximately equal in the early stage due to convection. However, when the gelatinization structure appears near the sidewall and top wall, the temperature drop rate is greatly different and the smaller the radius is, the faster the temperature drop rate is. Although the storage tank with a radius of 6 m has a small heat dissipation, its temperature drop rate is faster, which makes the crude oil in the tank more prone to gelation. Therefore, more attention should be paid to the insulation measures of small tanks and crude oil should be timely transported to large tanks. The top wall is the main area of heat dissipation, but the cooling oil sinks because of convection, resulting in a faster temperature drop of crude oil near the sidewall.

4.4 Analysis of the Effect of Different Periodic Change of Ambient Temperature

In order to verify the influence of ambient temperature on crude oil temperature field, three ambient temperatures were selected. The temperature of case 1 is shown in the formula 16. Case 2 is 2°C higher than the average temperature of case 1 and the temperature range is 2°C smaller. Case 3 is 4°C higher than the average temperature of case 1 and the temperature range is 4°C smaller. The temperature curve of case 1, case 2 and case 3 with time is shown in Figure 9.

As can be seen from Figure 7, the smaller the radius of the storage tank is, the faster the temperature drop rate is close to the sidewall and top wall. It can be considered that the temperature field in the tank is more affected in a small tank. Therefore, the cooling process of tanks with radius of 6 m under the periodic change of ambient temperature action of case 1, case 2 and case 3 is simulated to study the evolution rule of heat dissipation and average temperature at different positions. Figure 10 shows the heat dissipation at different ambient temperatures.
As can be seen in Figure 10, the heat dissipation at both the top wall and sidewall shows the same fluctuation characteristic. At different ambient temperatures, the heat dissipation near the top wall and sidewall maintains roughly the same trend. In case 1 with the lowest ambient temperature, the heat dissipation of the tank is relatively large. Compared with case 1, case 3 has a smaller fluctuation range of heat dissipation in the cooling process. It is due to the difference of periodic change of ambient temperature. The heat dissipation is related to the overall temperature of the outside. The overall temperature of case 1 is the lowest, so the overall heat dissipation of case 1 is the highest during the cooling process. With the ambient temperature changes periodically, the larger the fluctuation range of the ambient temperature is, the greater the fluctuation of heat dissipation will be. So case 3 has the smallest fluctuations in heat dissipation. Although the periodic change of ambient temperature has a certain influence on the heat dissipation at the top wall and sidewall, the influence is small and the difference in

**Figure 9.** The periodic change of ambient temperature as a function of time.

**Figure 10.** Evolution of heat dissipation of the tank with different periodic change of ambient temperatures.

**Figure 11.** Evolution of cooling rate at 0.05 m from the top wall and sidewall.
heat dissipation curve is not big. The difference of heat dissipation at the top wall is about 1 W/m², and the difference at sidewall is about 2 W/m² in the process of cooling.

The law of temperature drop rate at 0.05 m from the sidewall and top wall under different ambient temperatures is similar to that in Figure 8. After 40 h of temperature drop, the temperature drop rate under different ambient temperatures began to show fluctuation characteristics. During this time, case 1 has a faster temperature drop rate. After 40 hours, the temperature drop rate near the top wall and sidewall shows the similar law. In case 1, the temperature drop rate changes more significantly. In each temperature drop cycle, the temperature drop rate under case 1 condition is the largest when the outside temperature reaches the lowest, and the temperature drop rate under case 1 condition is the lowest when the outside temperature is the highest. And the temperature drop rate under case 1 has the largest variation range. It indicates that the average temperature of the ambient temperature will affect the average size of heat dissipation and temperature drop rate, while the fluctuation range of the ambient temperature will affect the fluctuation range of heat dissipation and temperature drop rate.

5. Conclusions

(1) The physical model and mathematical models of the static storage heat transfer process of waxy crude oil are established, the mathematical model is discretized and solved based on the finite volume method. This includes the use of volumetric force weighting method to deal with pressure interpolation. For the discretization of the transient term, the fully implicit first order temporal differentiation is used. The diffusive terms have been evaluated using a central differences scheme, while convective terms have been approximated by means of the QUICK scheme.

(2) The heat dissipation from oil in the calculation area is very sensitive to the ambient temperature. The heat dissipation presents a corresponding fluctuation with the ambient temperature, and gradually decreases with the cooling. At the same time, the heat dissipation of the top wall is larger and has greater fluctuation than sidewall.

(3) The cooling rate of oil in the calculation area is mainly affected by heat dissipation. The cooling rate fluctuates with the ambient temperature. When the oil starts to gel, the cooling rate rises sharply. The cooling rate near the sidewall is greater because of convection.

(4) Smaller tanks are more affected by the periodic change of ambient temperature. Large tanks dissipate more heat, but the smaller tanks have a faster temperature drop rate.

(5) Under the influence of different ambient temperatures, the average ambient temperature affects the overall heat dissipation and temperature drop rate, the lower the average temperature, the faster the temperature drop rate and the greater the heat dissipation. And the fluctuation range of ambient temperature affects the fluctuation range of heat dissipation and temperature drop rate, the larger the fluctuation range of ambient temperature is, the larger the fluctuation range of heat dissipation and temperature drop rate will be.

Conflict of Interest

There is no conflict of interest.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant No. 51704077).
This work was supported by the China Postdoctoral Science Foundation funded project (Grant No. 2018M640290).
This work was supported by the Postdoctoral Science Foundation funded project of Heilongjiang province.

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*Manuscript Received: Jul. 22, 2019
Accepted: Nov. 23, 2019*