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Numerical Study on the Static Cooling of Waxy Crude Oil in the Vault Tank

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ABSTRACT By means of additional specific heat capacity and momentum source terms methods, the physical and mathematical models of the heat transfer process of waxy crude oil during its static cooling in the vault tank are established. Through the numerical simulations for the cooling process of waxy crude oil in the vault tank, the detailed information about the flow field formed by natural convection together with the evolution of the temperature field is presented synchronously. Furthermore, more concern is taken on the evolution characteristics of the gelatinization structure of waxy crude oil and the relation between the distribution of the temperature field and flow field. Some conclusions include that it presents the significant coupling relationship between the natural convection and temperature field during the cooling. And the transition of the heat transfer mechanism from natural convection to heat conduction mainly contributes to the evolution of the thermal performance of waxy crude oil during its static cooling.

INDEX TERMS Waxy crude oil, vault tank, cooling, flow, gelatinization.

Nomenclature

C_{po}	specific heat of crude oil, J/Kg·°C
g	gravitational acceleration, m/s^2
H_{jc}	thickness of the foundation, m
H_{soil}	depth of the constant temperature layer, m
R_{soil}	external diameter of the soil region, m
r	radial coordinate
T_h	temperature of constant temperature layer, °C
T_o	oil temperature, °C
$T_{sidewall}$	temperature of the external wall of the sidewall, °C
$T_{soil,z}$	Soil isothermal layer temperature, °C
t	cooling time, s
u_0	initial axial velocity, m/s
v_0	initial radial velocity, m/s
λ_i	thermal conductivity of solid material, W/m·°C
λ_{roof}	thermal conductivity of tank roof, W/m·°C
λ_{soil}	thermal conductivity of soil, W/m·°C
ρ_o	Crude oil density at T_o, Kg/m^3
ρ'	Crude oil density at T', Kg/m^3
$f(r)$	total height of the tank, m
h_{roof}	surface heat transfer coefficient on the roof, W/m^2·°C
$h_{sidewall}$	surface heat transfer coefficient on the sidewall, W/m^2·°C
p	Pressure, Pa
$R_{\tan k}$	external diameter of the tank, m
T_{air}	atmospheric temperature, °C
T_i	temperature of solid material, °C
T_{roof}	temperature of the external wall of the roof, °C
$T_{soil,r}$	temperature of soil on the thermal influence boundary, °C
T_0	initial oil temperature, °C
u	axial velocity, m/s
v	radial velocity, m/s
x	axial coordination
λ_o	thermal conductivity of crude oil, W/m·°C
$\lambda_{sidewall}$	thermal conductivity of insulation, W/m·°C
μ_o	Crude oil dynamic viscosity, Pa·s
α	Thermal expansion coefficient, 1/K
T'	Density of crude oil at a given temperature, °C

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I. INTRODUCTION

Although in recent years, the outer floating roof tank has been widely used in large oil reserve projects, there are still a large number of vault tanks in service in oil field combined station, oil transfer station, oil field crude oil reservoir and long-distance oil pipeline station. It is of great significance for oil field production and stable supply of crude oil. For the vault tank, due to the existence of oil-gas space, the heat loss of the tank is much smaller than that of the floating roof tank, but the internal heat transfer law is more complicated, especially when the storage medium is waxy crude oil. With the temperature decreases, the waxy crude oil presents the poor and complicated fluidity. The complex physical properties of crude oil will do great harm to its economic and safe storage. It is of great significance for improving the safety of crude oil storage and reducing its heating cost to master the heat transfer law of waxy crude oil in the process of static storage. In addition, compared with the floating roof tank, the evaporation loss of the vault tank is more serious, and the evaporation loss is significantly related to the temperature distribution in the tank and the flow structure of the storage medium. Therefore, it is of more significance to study the heat transfer characteristics of the vault tank.

In general, the research on heat transfer characteristics of floating roof oil tank has obtained much attention. Although the structure of the vault tank and the floating roof tank is quite different, the methods and knowledge obtained in the study of the heat transfer characteristics of floating roof tank can certainly provide some reference and inspiration for the related research of the vault tank. Existing studies on the floating roof tank include: The method of numerical simulation is used to simulate the cooling process of waxy crude oil by the finite volume method by Cottor and Michae [1]–[3]. Oliveski *et al.* [4] has studied the heat transfer characteristics of natural convection in tanks by numerical simulation. Zhao [5], [6] studied the temperature distribution and cooling rule of waxy crude oil in tank by numerical simulation based on the new wavelet finite element method. And then Zhao *et al.* [7] uses the Gabor wavelet finite element to explain the oil tank stratification phenomenon effectively. Zhao *et al.* [8] studied the quantitative relationships of thermal characteristics under the different physical properties and to explore their quantitative relationship during the cooling. Li [9]–[11] studied the evolution of temperature distribution by the numerical simulation method and the test date of a large scaled floating roof tank. Shao [12] simulated the cooling process of a floating roof tank by Fluent to obtain the temperature distribution and flow pattern on different storage volume and height. Zhang *et al.* [13] numerical simulated the teat transfer process to explore the flow characteristics in large floating roof tank. Sun *et al.* [14] studied the temperature distribution in a 10^5 m^3 floating roof tank to discuss the effect of the variation of solar radiation. Mawire [15], [16] studied the heat losses in a small un-insulated oil storage tank by numerical simulation and experiment, the thermal gradient was evaluated in detail and the effects of ambient temperature and heat loss on the thermal gradient were studied. Then Mawire [17] studied delamination and heat loss of three hot oils in small tanks during 24-hour cooling. Vardar [18] studied the streamline, isotherm and average temperature changes of three inflow velocities and three heating conditions of high temperature fuel oil. Through the above research, the heat transfer and flow characteristics and other influencing factors in the tank are analyzed. Wang *et al.* [19], [20] described the temperature drop process of waxy crude oil in a double and single-deck floating roof oil tank by establishing mathematical and physical models. Then Wang *et al.* [21] experimented and simulated the heat transfer characteristics of waxy crude oil in a 10^5 m3 double-plate floating roof oil tank. Moreover, Zhao *et al.* [22]–[24] simulated the thermal and rheological property of waxy crude oil near gelatinization temperature by the additional specific heat capacity and momentum source terms methods. The evolution of temperature and flow distribution were discussed, and the influence of tube heating process to gelling structure and temperature distribution in the tank was discussed. And Zhang *et al.* [25] studied the cooling and gelatinization process of waxy crude oil in a single-deck floating roof tank during static storage by the finite volume method, which is similar to Zhao's research method. The numerical simulation for the long term storage of crude oil takes great effort and time. However, Turkyilmazoglu [26], [27] proposed an implicit numerical scheme for solving transient flows based on the spectral Chebyshev collocation technique in the direction normal to the disk and forward marching in time, which can better solve the magnetohydrodynamic time-dependent of von Karman flow. And Abid and Turkyilmazoglu [28] employ a special finite dierence method in association with the successive over-relaxation method (SOR) to numerically simulate the flow behavior. These researches definitely provide inspirations for the numerical simulation in this paper.

Although the research on the heat transfer of the floating roof tank can provide reference for that of the vault tank. Due to the difference between the structures of different kinds of tank, the existing research outcomes cannot be directly applied to the research of the vault tank. The structure of the vault tank has its own uniqueness, the heat dissipation loss of the top wall of the vault tank is much smaller than that of the floating tank, which leads to the special performance of the internal heat transfer and flow. In addition, the diameter of floating roof tank is generally much larger than its height, while the height of vault tank is generally larger than its diameter. This also lead to the different thermal performance for different kinds of tanks.

At present, there is little research on the heat transfer of crude oil in the vault tank. In the retrieved literatures, Rong *et al.* [29] based on the finite volume method, studied the cooling law during the static storage process of waxy crude oil in the vault tank. But the coupling relationship between the flow of waxy crude oil and heat transfer was not further explored. The deep analysis of heat transfer mechanism is limited. Based on the experimental analysis of the effects of ambient temperature, filling coefficient, wind speed change and volume change on the heat transfer coefficient of the vault tank, Chen and Shen [30]summarized the sensitive factors affecting the heat transfer coefficient of the vault tank. However, the temperature field distribution and flow characteristics of the storage medium in the vault tank were not analyzed. Based on the finite element method, Wang and Yin [31] calculated the internal pressure strength, stability and external pressure stability of the large vault tank. The results can provide a theoretical basis for engineering design, but this research mainly focuses on the mechanical characteristics of the vault tank.

Considering the scarce information in the literature on this research topic, the main purpose of this research is to investigate the coupled heat transfer and flow characteristics of waxy crude oil in the vault tank. And special concern is taken on the evolution of gelatinization of waxy crude oil. It is believed that through this research, the distribution and evolution law of temperature field of waxy crude oil in the vault tank can be obtained, which can provide a basis for the design of the heater in the tank. In addition, the optimal design of the insulating structure of oil tank can also be supported by this research. 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.

II. PHYSICAL MODELS

A. THERMAL SYSTEM AND COMPUTATIONAL DOMAIN

The object of study in this paper is a vault tank for storing waxy crude oil in Daqing oilfield, China. The vault tank diameter of 9 m, its height of 6.7 m, its center height of 9.7 m, its wall height of 8.7 m, its wall thermal insulation layer thickness of 60 mm, bottom base including asphaltic sand, sand layer, backfill soil layer, the thickness of 0.1 m, 0.3 m, 0.45 m respectively, its outside wall is concrete ring wall, the height is 0.85 m, 1 m wide. The average temperature of the research on heat transfer process for −20 °C, wind speed 7.9 m/s. During the storage of crude oil in the vault tank, since the oil temperature is significantly higher than the ambient temperature, a large amount of heat is transferred from the crude oil through the vault tank wall to the external atmosphere and the soil at the bottom of the vault tank.

Because the structure of the actual vault tank is very complex, it is difficult to simulate it directly. Under the premise of ensuring the calculation accuracy, it needs to consume a lot of calculation resources and time. In order to improve the computational efficiency, the coupling law of heat transfer and flow of waxy crude oil in the vault tank and the gelatinization behavior characteristics as the goals, and a certain hypothetical condition is introduced under the premise of retaining the characteristics of the body structure of the vault tank. The process of heat transfer for storage of waxy crude oil in the actual vault tank is simplified, including the following:

(1) The local structure and related accessories of the tank roof are neglected, including manhole, breather valve, temperature hole, etc. And consider that the roof of the vault tank is composed of equal thickness and homogeneous steel plates.

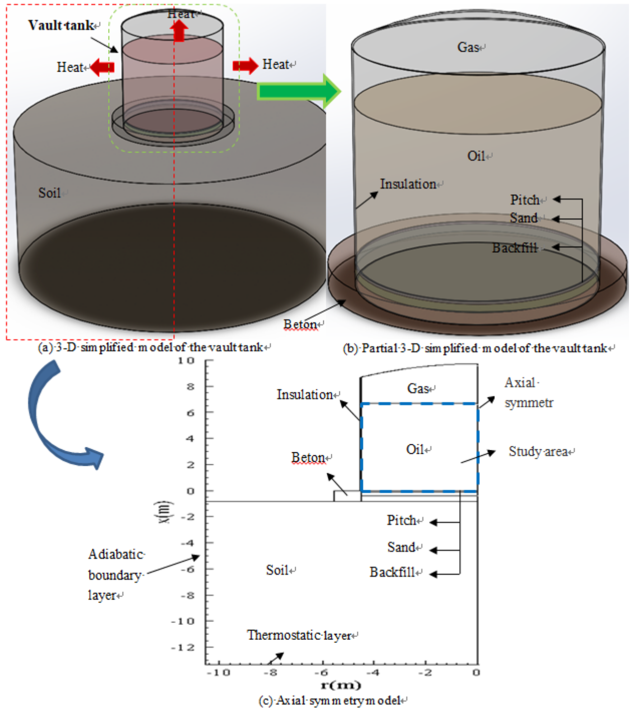

FIGURE 1. Physical models.

(2) The local structure and related accessories on the wall of the vault tank are neglected, including stiffening ring, spiral stairway, insulation material stent, the metal shield outside the insulation layer, etc. The vault tank wall is considered to be an equal thickness steel plate, and the outside of the vault tank wall is an equal thickness insulation layer.

(3) The local structure and related accessories at the bottom of the vault tank were neglected, including sacrificial anodic protection heating coil, etc. And the bottom of the vault tank is considered to be composed of a steel plate of equal thickness.

(4) It is considered that the base of the vault tank bottom is composed of three layers of materials of different thicknesses, the physical properties of the materials of each layer are constant, and the basic physical properties of the soil at the bottom of the vault tank are constant, and they do not change with time and location of storage.

(5) The heat transfer of crude oil in the vault tank has a certain influence range on the surrounding soil, which is the thermal influence part of the storage tank in the soil. If the soil is beyond this part, it is considered not affected by the vault tank. According to the existing relevant research, it can be considered that within 5 meters from the vault tank wall is the range of the thermal influence part. In addition, according to the field test results, there are constant temperature layer exist at the bottom of the vault tank. Soil temperature at 12.5 meters is almost the same all the year round, and it maintained at about 5 °C.

(a) Single-phase system (b) Crystallization and precipitation (c) Porous medium system

FIGURE 2. Evolution of the microstructure of waxy crude oil.

(6) On the basis of the above assumptions and simplified conditions simultaneously, the heat transfer and flow of crude oil along the circumferential direction of the vault tank are ignored, and the three-dimensional heat transfer problem of the actual vault tank is simplified as a two-dimensional heat transfer process with axisymmetric properties.

(7) There is oil-gas space above the oil in the vault tank. Generally speaking, at a lower ambient temperature, the oil-gas concentration and its physical properties in the oil-gas space are relatively stable during a certain period of time. Therefore, in order to improve the calculation efficiency, focusing on the heat transfer and flow of waxy crude oil and the detailed behavioral characteristics of the gelatinization process, the following two assumptions and simplifications are made:

① Calculate the physical properties of the mixed gas according to the physical parameters of the oil vapor and air and its concentration, and assume that the oil vapor and air in the oil-gas space are evenly distributed.

② The natural convection in the oil-gas space are neglected, the equivalent thermal conductivity is used to characterize the common heat transfer between natural convection and heat conduction in the oil-gas space. The equivalent thermal conductivity is obtained by modifying the heat conductivity of mixed gases based on the calculation results of the natural convection heat transfer correlation [8] in finite space.

Based on the above simplifications and assumptions, the physical model establishment process for obtaining the heat transfer problem of the actual vault tank storage waxy crude oil is as follows:

B. WAXY CRUDE OIL

During the storage, the physical properties of waxy crude oil become more and more complicated with the cooling progressing. So as to illustrate this characteristic, the evolution of microstructure of waxy crude oil produced in Daqing oil field is presented in Fig. 2.

When the temperature is high, the waxy crude oil is a single-phase system with a good fluidity (see Fig. 2(a)). However, when the temperature drops to the wax appearance temperature, the extensive crystallization and precipitation of paraffin begins (see Fig. 2(b)). During this process, the latent heat releases which affects the thermal properties. When this process takes a further step, with the amount of precipitated paraffin increases, the three-dimensional mesh structure of paraffin generates. The rheology behaviors of waxy crude oil change from Newtonian fluid into non-Newtonian fluid, and a large amount of latent heat releases. At this time, the waxy crude oil can still be seen as a single-phase system. When the temperature approaches to the losing flow point, the yield characteristic generates due to the increase of the wax-crystal structural strength (see Fig. 2(c)). The additional flow resistance generates which largely decreases the fluidity. At that moment, the waxy crude oil can be seen as a porous medium system in which the wax-crystal structure can be seen as the skeleton, and in which the liquid crude oil fills. When the flow resistance caused by the yield characteristic surpasses the buoyancy force induced from natural convection during the storage, the gelling of waxy crude oil begins.

Based on above analysis, the representation of physical properties of waxy crude oil is vital important for the simulation. During the calculation, the viscosity and specific heat capacity are set to be changed with temperature, so as to represent the variation of physical properties induced by the crystallization of paraffin.

When the temperature is lower than the abnormal point, the waxy crude oil belongs to the non-Newtonian fluid, and the viscosity of which is both affected by temperature and shear rate. However, since the variation of shear rate induced by natural convection is rather small, the viscosity data as a function of temperature at the low shear rate is used in the simulation (see Fig. 3(a). And these data of viscosity is measured by therheometer(Anton paar QC). Furthermore, on consideration of the latent heat released from the paraffin crystallization, the specific heat capacity of crude oil as a function of temperature in the large range from 6°C to 50°C is applied in the simulation so as to reflect the real thermal performance of waxy crude oil(see Fig. 3(b)). The latent heat caused by the paraffin crystallization is represented by additional specific heat capacity. As seen in Fig. 3(b), in the range of 24°C−44°C, the specific heat capacity increases gradually

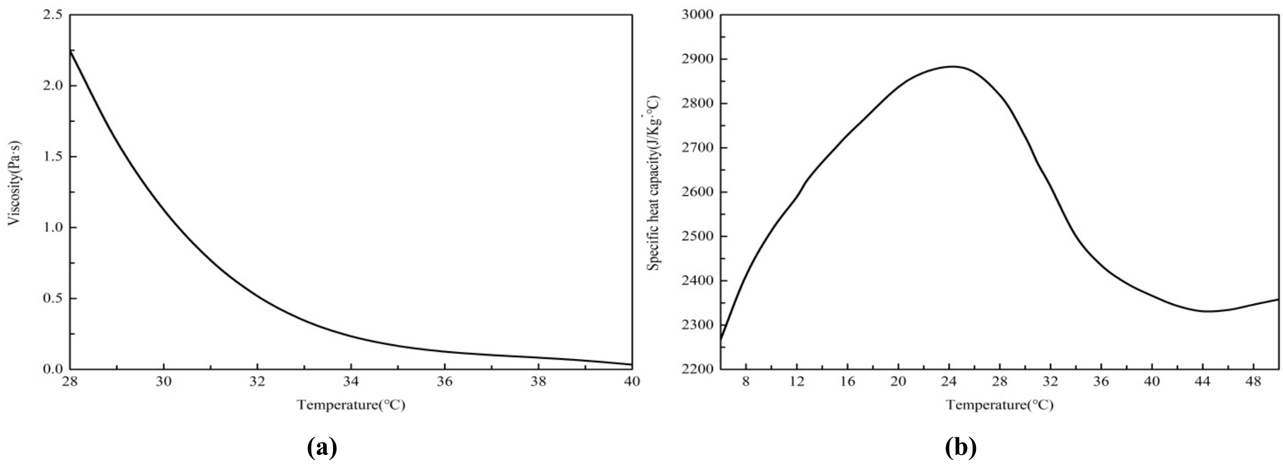

FIGURE 3. **(a) Viscosity as a function of temperature. (b) Specific heat as a function of temperature.**

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 specific heat capacity is measured by DSC (TA Q2000). The yield characteristic of waxy crude oil is represented by the sink term in the momentum equation which changes with temperature.

The density of crude oil is assumed as a constant except in the buoyance terms of the momentum equations (Boussinesq approximation). We have used the density meter (Anton Paar DMA 4500M) to measure the density of crude oil at different temperatures, and fitted the density data, finally obtained the functional relationship describing the change of crude oil density with temperature [22]. The result is shown in equation 1. The density of oil is 850kg/m^3 at 20 °C, and its coefficient of thermal expansion is 0.000844K^{-1}.

$$\rho_o = \rho' \left[1 - \alpha \left(T_o - T'\right)\right] \tag{1}$$

III. MATHEMATICAL MODEL, NUMERICAL APPROACH AND VERIFICATION PROCESS

A. MATHEMATICAL MODEL

The main controlling equations for flow and heat transfer of waxy crude oil during its static cooling are established and the boundary conditions and initial conditions are shown as follows [8], [22]:

1) FLOW AND HEAT TRANSFER EQUATION

The density of waxy crude oil changes with temperature and natural convection can be formed in static cooling process, during which the crude oil follows conservation of mass. Consequently, the continuity equation of waxy crude oil in the cylindrical coordinate can be described as follows:

$$\frac{\partial \rho_o}{\partial t} + \frac{\partial(\rho_o u)}{\partial x} + \frac{1}{r}\frac{\partial(\rho_o r v)}{\partial r} = 0 \tag{2}$$

The movement behavior of waxy crude oil is not only subjected to gravity, friction force and pressure because of the natural convection in static storage process, but also subjected to the extra resistance caused by formation of wax crystal when oil temperature is lower than losing flow point. As a result, the momentum equation of waxy crude oil in the cylindrical coordinate can be established as follows:

$$\frac{\partial(\rho_o u)}{\partial t} + \frac{\partial(\rho_o uu)}{\partial x} + \frac{1}{r}\frac{\partial(r\rho_o vu)}{\partial r} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}(\mu_o \frac{\partial u}{\partial x}) + \frac{1}{r}\frac{\partial}{\partial r}(r\mu_o \frac{\partial u}{\partial r}) - \rho_o g + S_u \tag{3}$$

$$\frac{\partial(\rho_o v)}{\partial t} + \frac{\partial(\rho_o uv)}{\partial x} + \frac{1}{r}\frac{\partial(r\rho_o vv)}{\partial r} = -\frac{\partial p}{\partial r} + \frac{\partial}{\partial x}(\mu_o \frac{\partial v}{\partial x}) + \frac{1}{r}\frac{\partial}{\partial r}(r\mu_o \frac{\partial v}{\partial r}) - \frac{\mu_o v}{r^2} + S_v \tag{4}$$

The additional flow resistance of waxy crude oil is represented by the sink terms of S_u and S_v in the momentum equations. The expressions of S_u and S_v are as follows:

$$S_u = -\frac{(1-\beta)^2}{(\beta^3 + 0.001)} C \cdot u \tag{5}$$

$$S_v = -\frac{(1-\beta)^2}{(\beta^3 + 0.001)} C \cdot v \tag{6}$$

Since the flow resistance of waxy crude oil increases with the temperature drops, the parameter β in the momentum source terms 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 β 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.

$$T_o > T_s, \quad \beta = 1 \tag{7}$$

$$T_o < T_z, \quad \beta = 0 \tag{8}$$

$$T_z < T_o < T_s, \quad \beta = \frac{T - T_z}{T_s - T_z} \tag{9}$$

Since the release of latent heat of wax crystallization will change the specific heat capacity of waxy crude oil, the actual measured data of specific heat capacity of waxy crude oil changing with temperature was used to conduct numerical simulation, and then the influence of latent heat of wax crystallization on the heat transfer process was expressed. According to the law of conservation of energy, the equation of temperature change in time and space of waxy crude oil is obtained:

$$\frac{\partial(\rho_o C_{po} T_o)}{\partial t} + \frac{\partial(\rho_o C_{po} u T_o)}{\partial x} + \frac{1}{r}\frac{\partial(r\rho_o C_{po} v T_o)}{\partial r} = \frac{\partial}{\partial x}(\lambda_o \frac{\partial T_o}{\partial x}) + \frac{1}{r}\frac{\partial}{\partial r}(r\lambda_o \frac{\partial T_o}{\partial r}) \quad (10)$$

In addition, the differential equations for heat conduction of different solid mediums are shown as follows:

$$\frac{\partial\left(\rho_i T_i\right)}{\partial t} = \frac{\lambda_i}{C_{pi}}\left(\frac{\partial^2 T_i}{\partial x^2} + \frac{1}{r}\frac{\partial T_i}{\partial r} + \frac{\partial^2 T_i}{\partial r^2}\right) \quad (11)$$

2) BOUNDARY CONDITIONS

External surface of the tank roof:

$$x = f\left(r\right), \quad -R_{\text{tank}} \le r \le 0, \quad -\lambda_{\text{roof}}\frac{\partial T_{\text{roof}}}{\partial x} = h_{\text{roof}}\left(T_{\text{air}} - T_{\text{roof}}\right) \quad (12)$$

External surface of the sidewall:

$$0 \le x \le H_{\text{sidewall}}, \quad r = -R_{\text{tank}}, \quad -\lambda_{\text{sidewall}}\frac{\partial T_{\text{sidewall}}}{\partial r} = h_{\text{sidewall}}\left(T_{\text{air}} - T_{\text{sidewall}}\right) \quad (13)$$

Thermal influence boundary on horizontal direction:

$$-\left(H_{\text{jc}} + H_{\text{soil}}\right) \le x \le -H_{\text{jc}}, \quad r = -R_{\text{soil}}, \quad -\lambda_{\text{soil}}\frac{\partial T_{\text{soil,r}}}{\partial r} = 0 \quad (14)$$

Constant temperature layer:

$$x = -\left(H_{\text{jc}} + H_{\text{soil}}\right), \quad T_{\text{soil,z}} = T_{\text{h}} \quad (15)$$

Symmetry plane:

$$-\left(H_{\text{jc}} + H_{\text{soil}}\right) \le x \le H_{\text{center}}, \quad r = 0, \quad -\lambda_i\frac{\partial T_i}{\partial r} = 0 \quad (16)$$

The boundary conditions of the soil surface and other boundaries in contact with the atmosphere are similar to those of the vault tank roof and the vault tank wall and are treated in accordance with the third type of boundary conditions.

3) INITIAL CONDITIONS

At the initial time, the crude oil is still and the oil temperature in the tank is homogeneous. The temperature distribution of solid media such as soil can be calculated according to the steady temperature heat transfer process according to the oil temperature.

$$\text{Initial condition} \quad T_o(r,x) = T_o, \quad T_i(r,x) = f(r,x), \quad u_o(r,x) = v_o(r,x) = 0 \quad (17)$$

TABLE 1. Comparison between results from numerical simulation of different mesh width in sidewall.

Oil T（□）	Sidewall T（□）	Nu（mesh1）0.1mm	Nu（mesh2）0.25mm	Relative error between mesh1 and mesh2 %	Nu（mesh3）0.5mm	Relative error between mesh1 and mesh3 %
40.0	10	2073.8287	2094.3147	0.99%	2097.7317	1.15%
39.5	10	590.9059	597.5779	1.13%	703.7451	19.10%
39.0	10	600.5276	603.1375	0.43%	717.4910	19.48%
38.5	10	610.7922	613.8757	0.50%	727.8640	19.17%
38.0	10	619.9209	622.4524	0.41%	738.6321	19.15%
37.5	10	628.5841	630.8990	0.37%	749.0889	19.17%
37.0	10	636.7515	637.6996	0.15%	759.1189	19.22%
36.5	10	644.3724	645.0704	0.11%	769.2770	19.38%
35.5	10	650.0467	652.0574	0.31%	775.9890	19.37%
35.5	10	658.2763	659.4031	0.17%	783.8058	19.07%

B. NUMERICAL APPROACHES

1) DISCRETIZATION OF COMPUTATIONAL REGION

In order to select the best mesh system based on the calculation efficiency and precision, three sets of mesh systems with different numbers and layout strategies were designed. The difference is reflected in the setting of the minimum mesh size near the top of the vault tank and the wall of the vault tank. The three sets of schemes are: 0.1mm, 0.25mm and 0.5mm, and the growth ratio of the mesh adopted by different schemes the same.

In order to compare the calculation results of different meshes, the numerical simulation of the heat transfer process of the vault tank at the initial oil temperature of 40 °C and the ambient temperature of −20°C was carried out with three mesh systems, and the results of Nu numbers due to the loss of heat to the environment from the sidewalls for different mesh systems are shown in Table 1:

According to the data in the table, the Nu number calculated by three different mesh systems is not much different, and the calculation result of the minimum mesh number of 0.1mm and 0.25mm is closer, There is a big gap between the results of the mesh with the minimum scale of 0.5mm.Therefore, in order to improve the calculation efficiency, it is more suitable to use a mesh system with a minimum mesh width of 0.25 mm.

Based on above analysis, and taking into consideration of the structural feature of the thermal system, the detailed designing scheme of mesh for the entire calculation domain is shown in Fig. 4(a), and that for crude oil is shown in Fig. 4(b). For the calculation domian of crude oil, the structural quadrilateral mesh is used. And the mesh near the inner surface where the crude oil is in contact with the oil-gas space, the sidewall and the base wall are locally concentrated. After the mesh refinement, the minimum mesh size in the calculation domian of crude oil is 0.25mm. And then the mesh size is gradually increased toward the center of the calculation domian of crude oil at a ratio of 2%. For the calculation domian of solid mediums, including the domain where the oil-gas space is located, based on the mesh density and size in the calculation domain of crude oil, the closer the distance is to the crude oil domain, the denser the mesh distribution is. And away from the crude oil domain, the more sparse the mesh distribution is. In addition, due to the significant heat exchange, the mesh refinement is also performed in

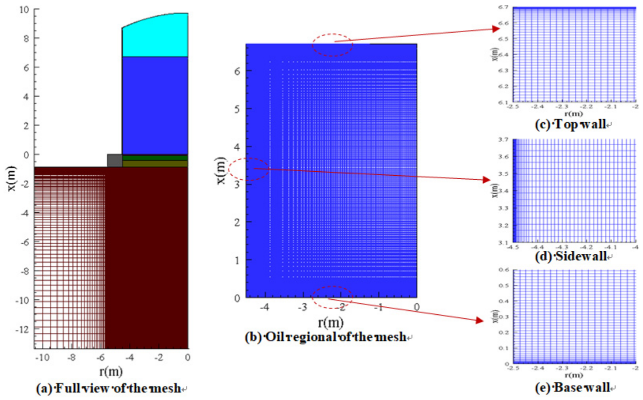

FIGURE 4. Mesh system for the calculation domain.

the region where the oil-gas space is in contact with the inner surface of the tank top. Based on this design scheme, the total number of meshes in the calculation domian of crude oil is 172480. And the total number of meshes in the axial derection is 560, in the radial derection is 308. The total number of meshes in the domain of oil-gas space is 107800. And that in the axial derection is 350, in the radial derection is 308. The total number of meshes in the domain of insulating layer is 36400. The total number of meshes in the domain of concrete ring wall is 10800. The total number of meshes in the domain of foundation is 36960. The total number of meshes in the domain of soil is 47080. Finally, the total number of meshes in the entire calculation domain is 411520.

2) 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 [32], [33] 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) TIME STEP CHOSEN

Due to the large geometric size of the calculation domain, the cooling process of the crude oil is slow. Therefore, in the numerical calculation process, in order to balance the calculation efficiency and accuracy, the numerical discretization is

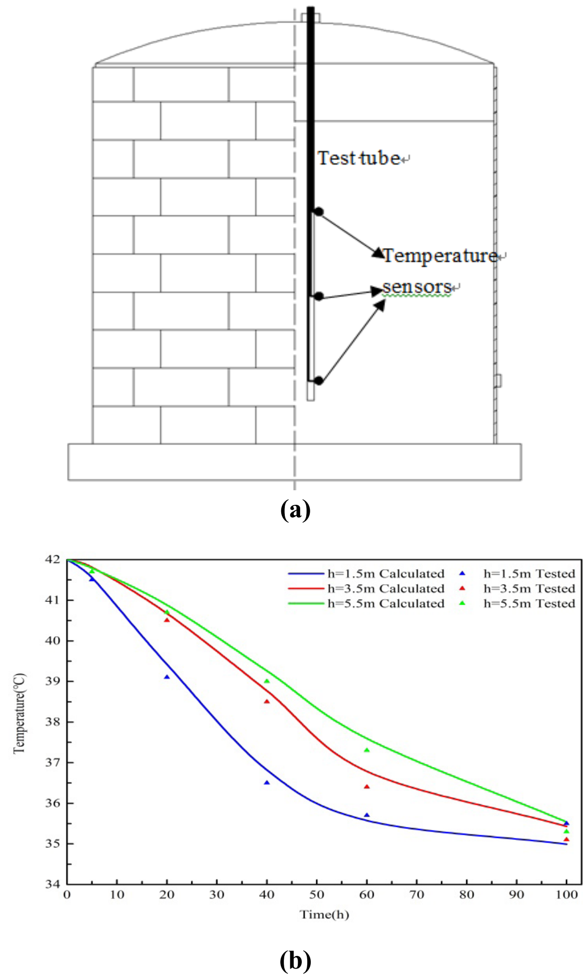

FIGURE 5. (a) Schematic of vault tank. (b) Comparison of results.

performed at different time steps. The specific method is: in the initial stage of calculation, the non-steady-state numerical simulation is performed with a time step of 0.5 s, which can keep the calculation process stable, and each step can quickly converge. Therefore, the time step is gradually increased to 0.8s and 1s, and the calculation process is still stable, but the number of iteration steps required for convergence increases. However, as the cooling progresses, the natural convection in the vault tank is weakened, and the coupling between the flow and heat transfer is weakened, so the solution process tends to be stable. Therefore, the time step in the subsequent calculation process is 1 s.

C. VERIFICATION PROCESS

The process of verification for numerical solutions is important. So the test date is collected to testify the reliability of numerical solutions. The experimental procedure is illustrated in Fig. 5(a).

The verified temperature data comes from a temperature measuring device installed in the 500m^3 vault tank at an oil transportation station. The vault tank has a center height of 9.89 meters, the vault tank wall height of 9.1 meters and a diameter of 8.92 meters. The test part is a temperature measuring rod with anti-static and explosion-proof properties. A plurality of PT100 temperature sensors with an accuracy of 0.1 °C is installed at different positions in the temperature measuring rod, which can obtain oil temperature data at different heights in the vault tank in real time. The transmission and storage function of the collected data can be completed. The data collected by the three temperature sensors 1.5m, 3.5m, and 5.5m from the bottom of the temperature measuring rod are selected as the data source for verification. Before the on-site static storage experiment of the vault tank, the central oil temperature in the vault tank was 42.3 °C, and the average temperature during the test period was −18.6°C. Fig. 5(b) shows the comparison of field test data with numerical simulation data under the same operating conditions. It can be seen from Fig. 5(b) that the numerical simulation results are in good agreement with the field test results. The two not only have the same trend with the storage time, but the average error during the test is only 0.64%, the maximum error is 3.49%, the minimum error is 0.53%, and the numerical simulation results have higher calculation accuracy. It can be seen that the established mathematical model and numerical simulation method are suitable for the study of heat transfer process of crude oil in the vault tank.

IV. RESULTS AND DISCUSSION

A. SIMULATION CASES

The vault tank is 9 meters in diameter and 6.7 meters in height. The initial oil temperature is 40°C and the ambient temperature is −20°C. Heat conduction and convection are the ways of heat dissipation.

B. THERMAL CHARACTERISTICS OF WAXY CRUDE OIL DURING ITS STATIC COOLING

1) EVOLUTION OF TEMPERATURE FIELD, VELOCITY FIELD AND THE GELATINIZATION STRUCTURE OF CRUDE OIL

Due to the coupling of heat transfer and flow during storage, it is necessary to synchronize the evolution process of temperature field to give the flow field information formed by natural convection of crude oil in storage tank in order to analyze the heat transfer laws and formation mechanism of crude oil. Therefore, the numerical simulation results of the temperature and velocity fields of study area at different times are shown in Figs. 7 and 6. For waxy crude oils, with its temperature change, it will change from a sol state to a nearly solid gel state, which is affected by the temperature field and velocity field distribution and its changes, while the change in crude oil state will also affect its flow and the evolution of the temperature field has an impact. Therefore, along with the temperature field and flow field data, the evolution process of the gelatinization structure formed by the waxy crude oil in the study area at different times is given, as shown in Fig. 8.

It can be seen from Fig. 7(a) that at 1h, the oil temperature in the vault tank is not significantly reduced, the oil temperature is very high and the distribution is very uniform, and the oil temperature near the oil-gas interface and the vault tank wall is significantly reduced. As the oil temperature in the local part decreases, the density increases and begins to settle to the bottom of the vault tank, resulting in a change in the pressure distribution inside the vault tank. The flow field structure formed by the natural convection of the crude oil begins to appear obvious, as seen in Fig. 6(a). There are multiple flow vortices in the vault tank. At this time, since the oil temperature at different positions in the vault tank is much higher than the gelatinization temperature of the crude oil, there is no the gelatinization structure in the vault tank (Fig. 8(a)).

Thereafter, as the temperature drop progresses, the oil temperature at the surface oil surface and the vault tank wall decreases more significantly. The cold oil formed by the cooling and its sedimentation behavior enhance the natural convection effect inside the vault tank. At the same time, under the action of natural convection, a large amount of low-temperature crude oil settles to the bottom of the vault tank, resulting in the accumulation of cold oil in the part where the bottom of the vault tank is in contact with the vault tank wall, and the significant oil temperature stratification distribution occurs in the lower part of the vault tank. Characteristics (Fig. 7(b)). The deposition of cold oil in the contact part between the bottom of the vault tank and the wall of the vault tank also led to the first occurrence of gelatinization in this part (Fig. 8(b)). This phenomenon indicates that natural convection is important in the formation of the gelatinization structure in the vault tank. effect. In terms of the flow structure alone, the convection in the vault tank is very intense at this time, which is characterized by a large vortex in the middle and upper part of the crude oil controlling the overall flow of the crude oil, which dominates the deposition of cold oil and the floating behavior of the hot oil. There are also several small vortices around the large vortex that affect the local flow and local temperature distribution of the crude oil (Fig. 6(b)). Along with the natural convection, the oil temperature near the bottom of the vault tank is significantly reduced, resulting in a significant increase in the viscosity of the crude oil in the corresponding part, and the convection effect is weakened, and the flow velocity is significantly reduced.

With further development of the temperature drop process, the whole vault tank is characterized by stratified distribution under the action of natural convection, and the cold oil is continuously deposited on the bottom of the vault tank, resulting in the upward expansion of the low temperature part in the vault tank. Wherein, the temperature of the crude oil located in the contact part between the bottom of the vault tank and the wall of the vault tank is further lowered, and the low temperature part gradually expands toward the bottom of the vault tank, forming a low temperature layer at the bottom of the vault tank, accompanied by the generation and development of the low temperature layer, the part occupied by the gelatinous crude oil in the tank is gradually overlaid to the bottom of the tank. The part occupied by crude oil

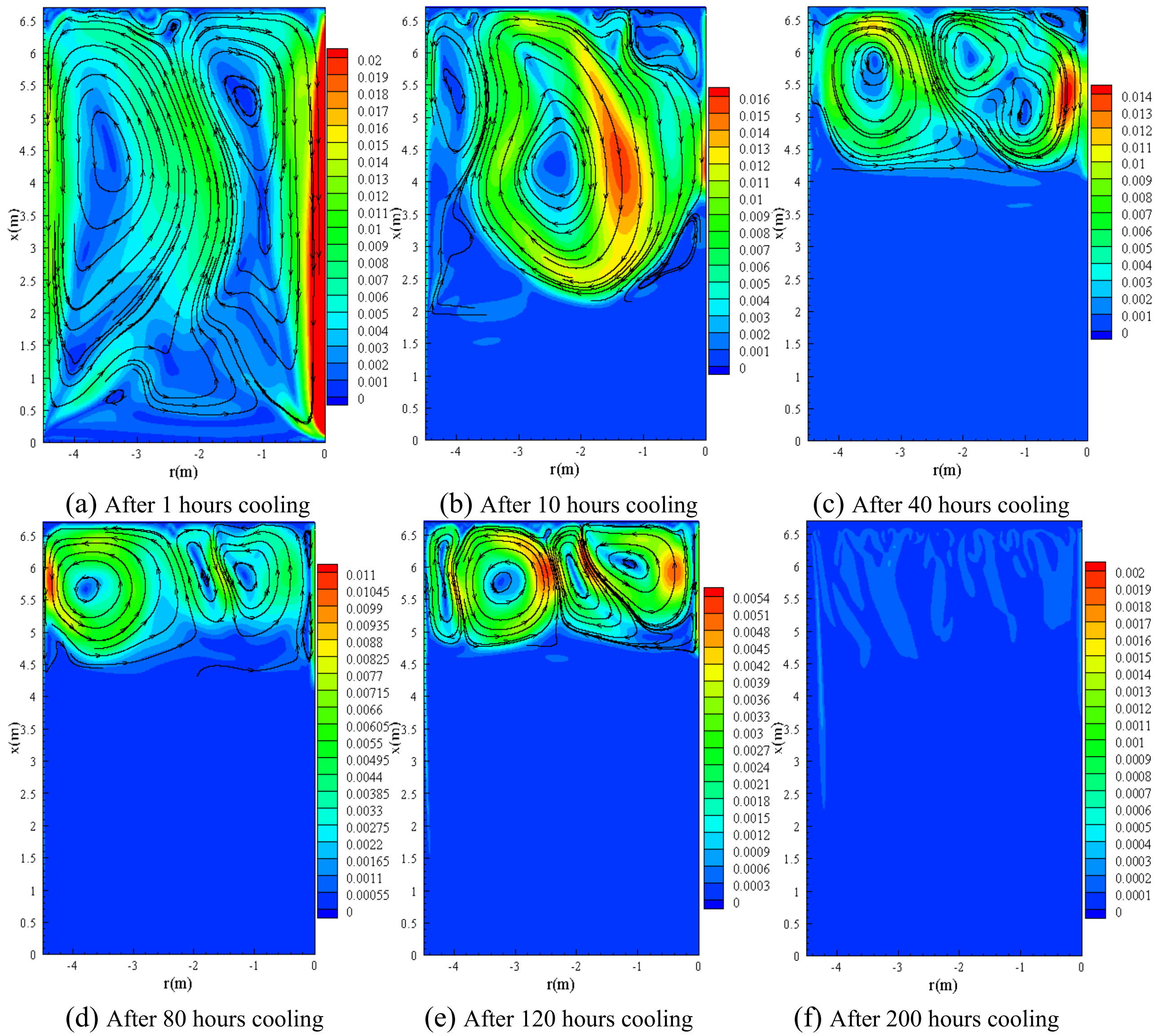

FIGURE 6. Evolution of the velocity magnitude and vectors of waxy crude oil.

is gradually covered to the bottom of the vault tank. At the same time, the part occupied by gelled crude oil also has a tendency to develop upward along the vault tank wall. Further, it can be seen from Fig. 8(d) that there is a transition layer having a thickness of about 0.8 m above the vault tank bottom gelatinization part, and the crude oil in this part is in a transition state between the sol and the gel. At the same time, this part is also a potential part for the formation of gelatinization structures. It should be noted that the inlet and the outlet of the vault tank is generally located at a position more than 1 m from the bottom of the vault tank. This position is a position that needs special attention in the actual operation and management of the vault tank. Once the gelatinization structure covers the part, it may hinder the vault tank 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, and the algebraic system of equations resulting for each variable has been solved by using a multigrid method from being sent and received. The oil process proceeds normally. At this stage, as the oil temperature in the vault tank decreases, the viscosity of the crude oil increases, the convective flow of the crude oil decreases significantly, and thepart covered by the natural convection gradually weakens (Fig. 6(c), (d)).

When the temperature drop reaches 120 h, the low temperature part in the vault tank is further enlarged. The high temperature part mainly occupies the upper part of the crude oil and has a further shrinking trend (Fig. 7(e)). The high temperature part is liquid crude oil, and the convection mainly

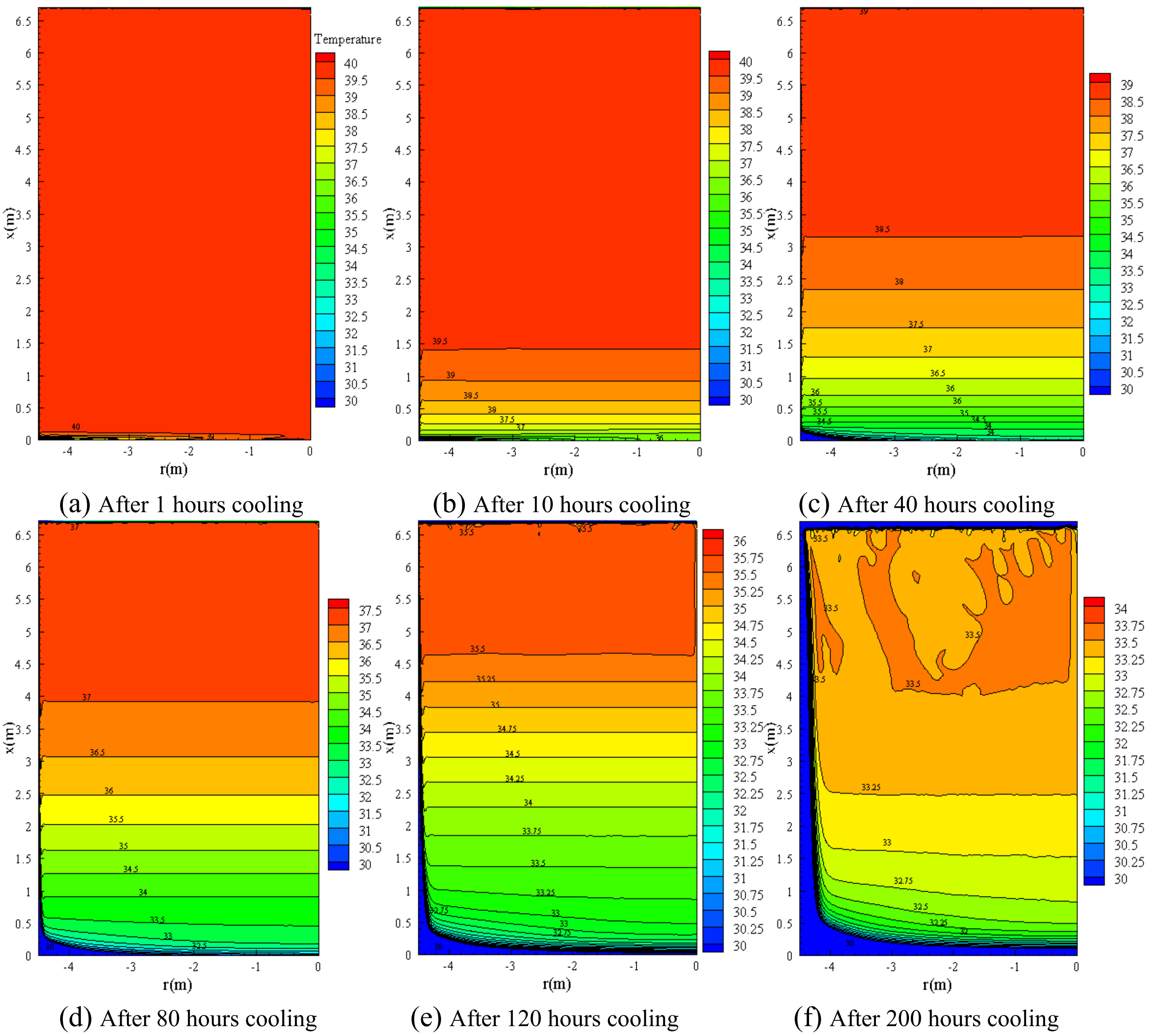

FIGURE 7. Evolution of the temperature distribution of waxy crude oil.

occurs in this part, but in the early stage of temperature drop, the oil temperature in the part is also significantly reduced, and the viscosity of the oil increases, resulting in a significant decrease in convection in the part. Thereafter, as the temperature drop develops further, the high temperature part in the vault tank and the part covered by convection will be further reduced (Fig. 6(e)), and the low temperature part will be further expanded. As shown in Fig. 8(e), when the temperature drop is to 120 h, a complete gelatinization layer has been formed at the bottom of the vault tank, and the thickness of the overlying layer on the vault tank has also increased to about 2m. At the same time, the gelatinization structure also advances along in the vault tank wall, resulting in the gelatinization structure in the part where the bottom of the vault tank is in contact with the vault tank wall is significantly enhanced.

When the temperature drop progresses to 200 h, there is no pure liquid crude oil in the vault tank. The crude oil part is transformed into a shell with gelatinization structure. The internal oil is in a state of transition between gel and sol. The overall oil temperature distribution is gradually reduced. It is transformed from a layered distribution controlled by natural convection to a distribution characteristic controlled by the interaction of natural convection and heat conduction. At this time, the oil temperature at different positions in the vault tank drops significantly, and the relatively high temperature part is mainly concentrated in the upper part of the crude oil (Fig. 7(f)). The oil in the vault tank is greatly viscous due to the decrease in temperature. When it is raised, crude oil is almost no liquidity (Fig. 6(f)). At this time, in the formed gelatinization structure, the tank top and the vault tank bottom have a relatively uniform thickness of the gelatinization layer,

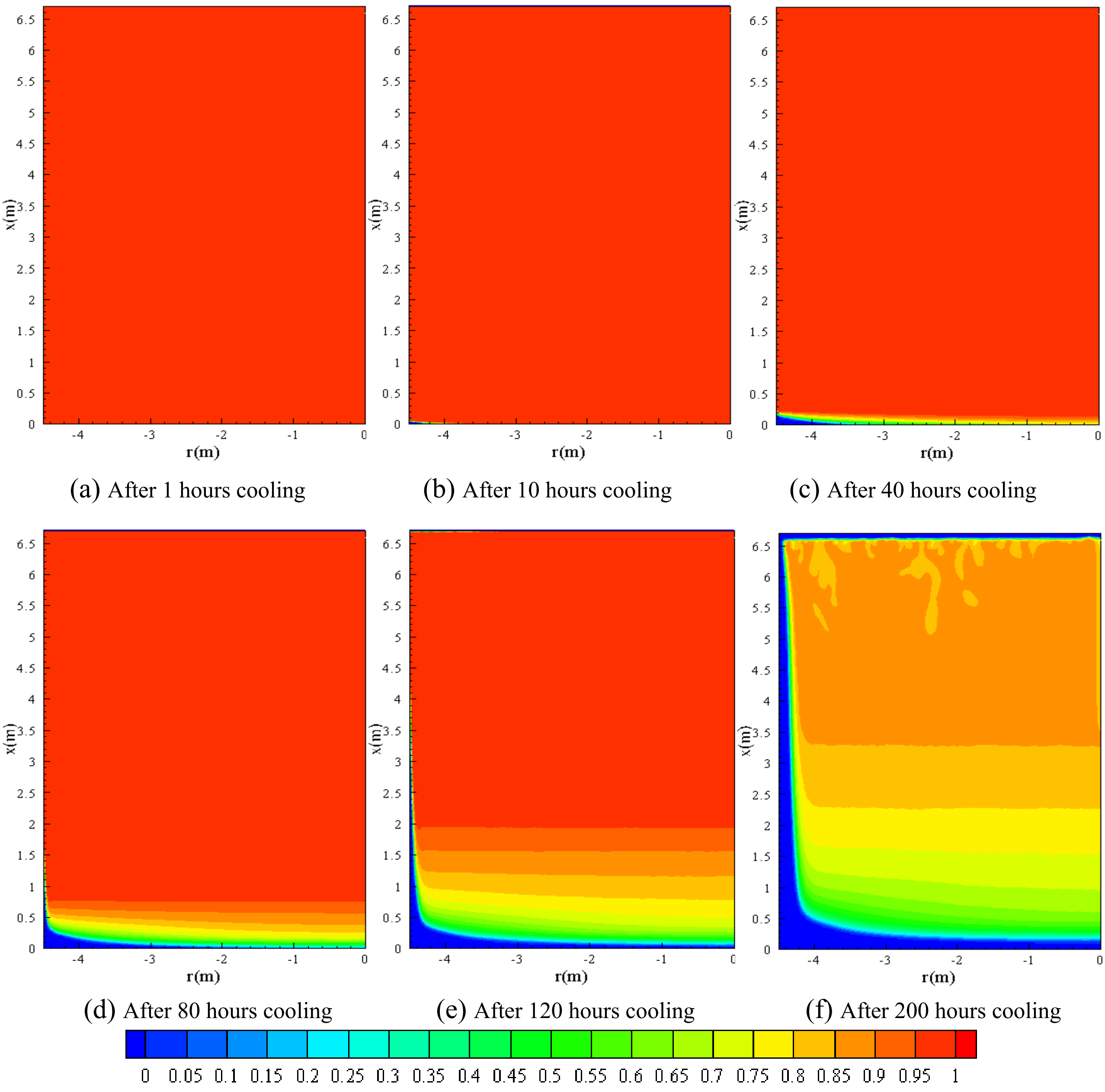

FIGURE 8. Morphology evolution of gelled crude oil.

and the thickness of the gelatinization layer of the vault tank wall is unevenly distributed, and the closer to the tank bottom, the thicker the gelatinization layer is, which is affected by natural convection. Distinctive features. Due to the formation of the gelatinization structure, the heat transfer mode in the vault tank will gradually evolve to be completely controlled by heat conduction, and the temperature drop process of the crude oil will be significantly slowed down, and the low temperature part near the vault tank wall, the vault tank bottom and the oil-gas interface will further the center advances and eventually the crude oil in the vault tank will be completely congealed.

2) OIL AXIAL VELOCITY ANALYSIS

During the temperature drop of crude oil storage in the vault tank, the cold oil deposit and the hot oil float are the main forms of macro-flow of crude oil, which directly determines the oil temperature distribution and the formation and evolution of the gelatinization structure. Therefore, the distribution curves of the axial velocity at different radial positions in the vault tank at different times with the height of the crude oil are extracted as shown in the Fig. 9:

As can be seen from the figures, at a certain radial position, the axial velocity direction of crude oil changes alternately for

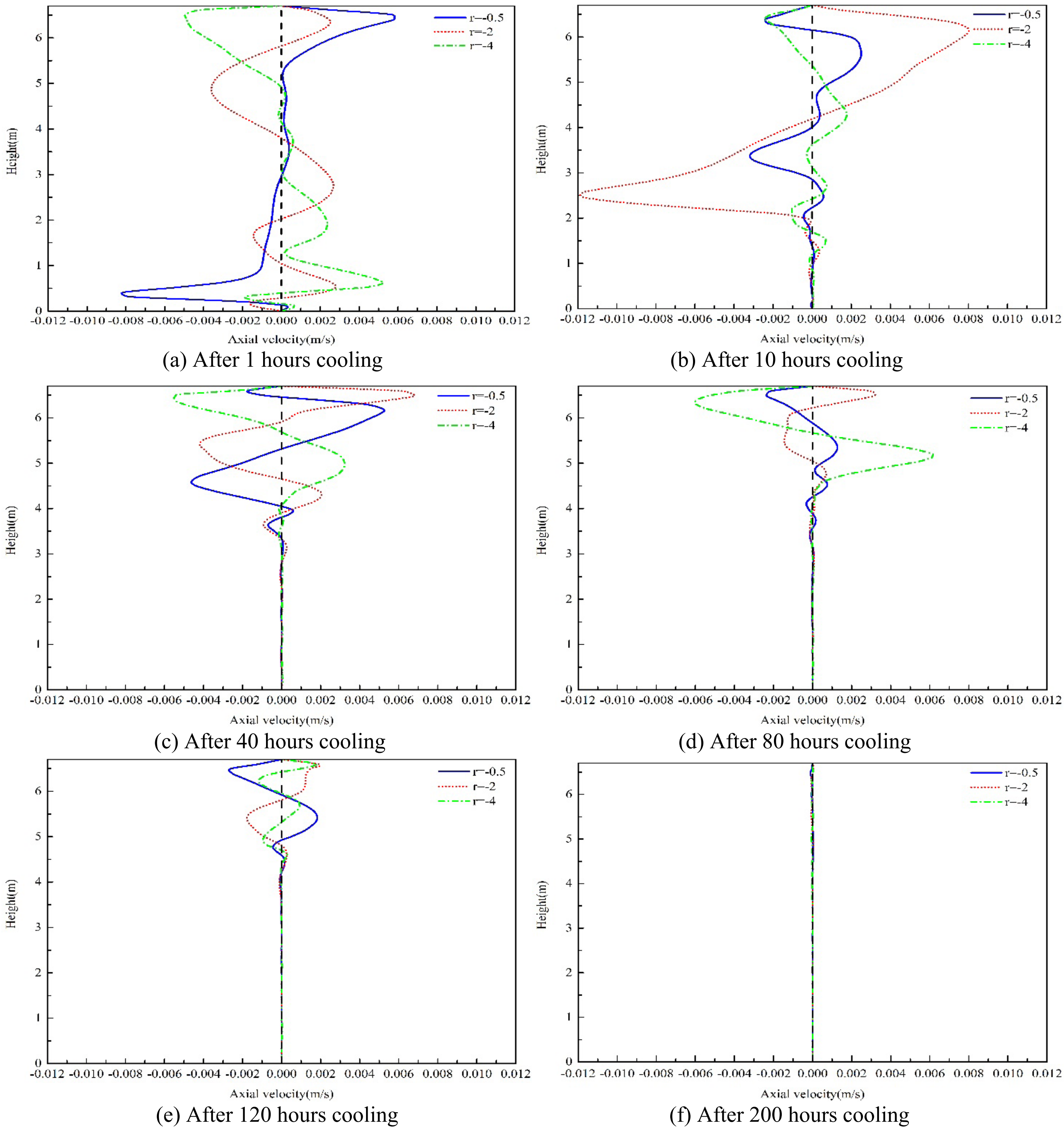

FIGURE 9. **Axial velocity along the axial direction of the tank on different radial position at different cooling time.**

many times, which means that there are many whirlpools with different flow directions in the vault tank. It indicates that the internal flow change of crude oil is very complex. It can be further speculated that the more frequently the direction of axial velocity changes, the more intense the flow of crude oil, the stronger the convection. Therefore, as can be seen from the above figures, the flow in the vault tank is weak at the initial stage of temperature drop. As the temperature drop continues, the flow in the vault tank is strengthened, especially the convection near the oil-gas interface and the middle part is more significant than that at the vault tank bottom (Fig. 9 (a), (b)). The axial velocity changes more frequently, the velocity value is larger, and there are many obvious flow vortices in these parts. However, because the convection accelerated the temperature drop of crude oil, the convection part in the vault tank decreased significantly with the temperature drop, and the flow velocity in the convection part also decreased significantly, and the flow intensity

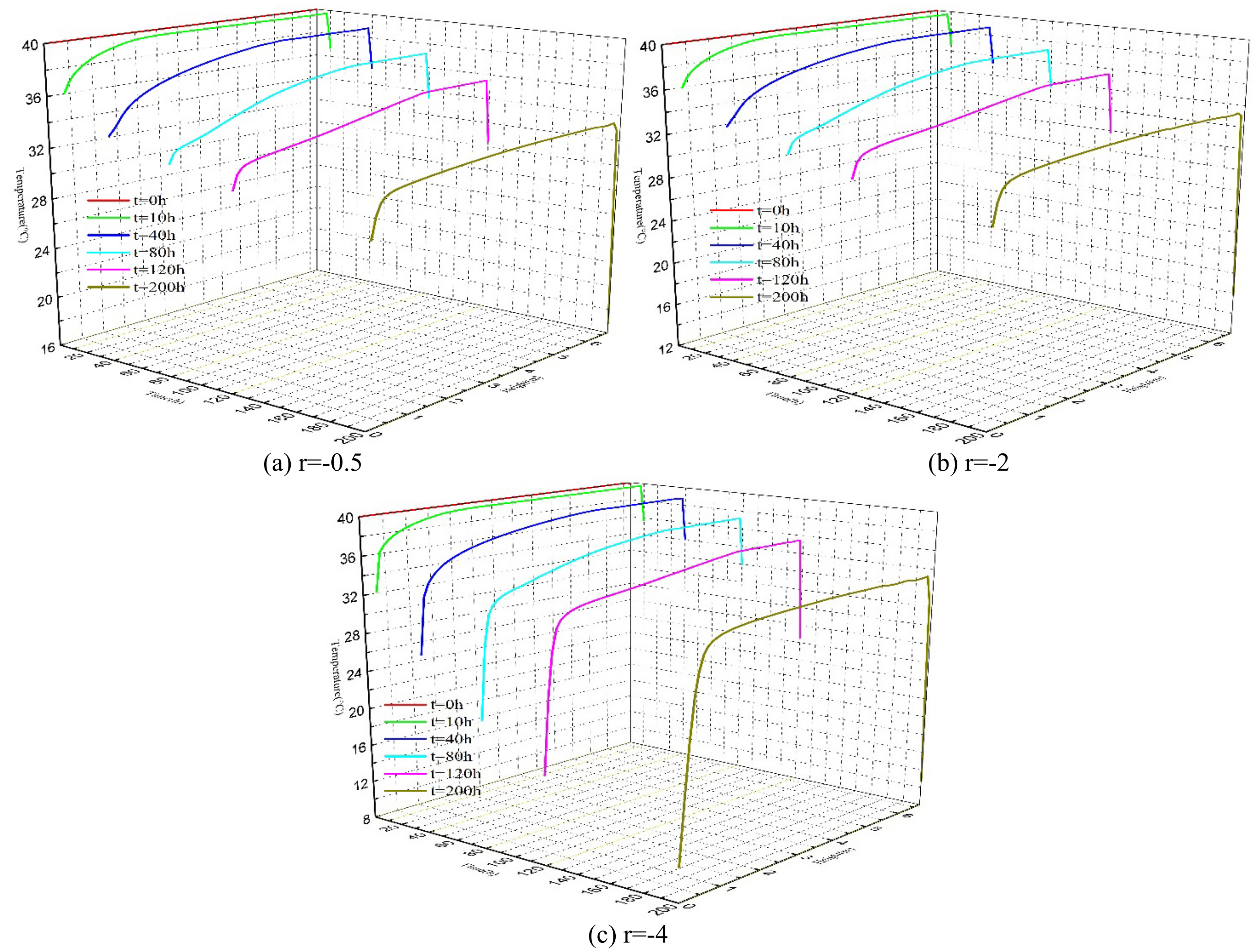

FIGURE 10. **Temperature distribution vs. cooling time along the axial direction on different radial position.**

also weakened significantly. Relatively speaking, the oil temperature near the bottom of the vault tank decreases more significantly due to the deposition of cold oil, which leads to the extremely significant attenuation of the axial velocity of crude oil near the bottom of the vault tank. At the end of temperature drop (200h), the axial velocity of crude oil at each radial position of the vault tank is close to 0, which is caused by the overall temperature of crude oil lower than the losing flow point (Fig. 9 (f)).

By comparing the axial velocity distribution of crude oil in different radial positions, it is found that the axial velocity of crude oil in the part near the vault tank wall is greater than that in the center of the vault tank during the initial stage of temperature drop. But at the end of temperature drop, the axial velocity of crude oil in the part near the vault tank wall is less than that in the center of the vault tank. This is because the formation of convection at the vault tank wall is caused by the sinking of cold oil in the vault tank wall. At the initial stage of temperature drop, the temperature difference between the vault tank wall and the outside world is large, resulting in strong convection. However, the convection accelerates the temperature drop of crude oil, resulting in the increase in oil viscosity in the vault tank. The temperature drop of the oil near the vault tank wall is faster, and it causes the axial speed to decay more quickly.

3) OIL AXIAL TEMPERATURE ANALYSIS

Fig. 10(a), 10(b) and 10 (c) show the axial temperature of oil along different radial positions of the vault tank.

In order to further explain the oil temperature distribution in the vault tank and its evolution law during the temperature drop process, the axial temperature distribution data of different radial positions in the vault tank are extracted, as shown in the figures:

As shown in Fig. 10(a), 10(b) and 10(c), the axial temperature distribution and its evolution law at different radial positions in the vault tank are basically similar during the temperature drop. According to the temperature data shown in the figures, the crude oil vault tank be divided into four parts along the axial direction of the vault tank: ① low temperature part near the bottom of the vault tank, ② temperature transition part, ③ high temperature part of the vault tank center, ④ low temperature part in contact with the oil-gas space.

In the initial stage of temperature drop(t = 1, t = 10), four parts with different temperature distribution characteristics are very obvious along the reservoir axis. Relatively speaking, the high temperature part occupies the largest space. And this part is not only the highest temperature, but also the most uniform temperature distribution in this part, this part is located in the upper part of the vault tank. The second is the temperature transition part located in the lower part of the vault tank, which is the transition part between the high temperature part and the low temperature part at the bottom of the vault tank. The low temperature part of the vault tank bottom occupies less space than the transition part, but is larger than the low temperature part that comes into contact with the oil-gas space, and the oil temperature in the vault tank bottom part is the lowest. Relatively speaking, the part of low temperature part in contact with the oil-gas space is the smallest, but its temperature gradient is the largest. With the progress of the temperature drop process (t = 40, t = 80, t = 120), the space occupied by the temperature transition part increased significantly, which was mainly caused by the deposition of low temperature crude oil caused by the natural convection in a large range at the bottom of the vault tank. In addition, the temperature variation in this part significantly increased, which was related to the slow decline of oil temperature in the high temperature part and the accelerated decline of oil temperature in the low temperature part at the bottom of the vault tank. Compared with the increase of the temperature transition part, the space occupied by the high temperature part decreased significantly, while the space occupied by the low temperature part close to the oil-gas interface and the vault tank bottom did not change significantly, but the oil temperature decreased significantly. Relatively speaking, the oil temperature near the oil-gas interface decreases the fastest. As the temperature drop continues, the axial high temperature part and the temperature transition part basically merge due to the recession of natural convection, and become a relatively gentle temperature distribution transition part, which is connected to the low temperature part at the bottom of the vault tank and the low temperature part close to the oil-gas space. At this time, due to the control of thermal conductivity and the lack of thermal insulation effect on the top of the vault tank, the heat loss is much higher than that on the vault tank wall and the vault tank bottom, resulting the oil temperature drop is most significant in the low temperature part close to the oil-gas space, making this part the lowest temperature part in the vault tank. By comparing Fig. 10(a), (b) and(c), the axial temperature distributions of the different radial positions are generally the same, but there are also certain differences: the basic feature is that the closer to the vault tank wall, the lower the temperature of the cryogenic part at the bottom of the vault tank, and the greater the coverage of the cryogenic part. This feature runs through the entire temperature drop process and it is caused by the natural convection of crude oil. This feature can also be found in the front temperature and the gelatinization structure cloud map. Moreover, according to the above figures and the cloud map of temperature and the gelatinization structure, the part where the vault tank wall and the bottom of the vault tank come into contact with each other is always the part with the most significant minimum temperature and gelatinization structure in the vault tank, and the existence of this part needs to be given sufficient attention.

V. CONCLUSION

(1) The physical model and mathematical model of the static storage heat transfer process of waxy crude oil in the vault tank 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. The first-order all-implicit discrete format is used to discrete time terms, the central difference format discrete diffusion term, the QUICK discrete pair flow term, and the solution of discrete algebraic equations based on multiple mesh methods.

(2) The heat transfer mechanism and boundary conditions dominate the distribution and evolution of temperature field and flow field of crude oil in the vault tank, and further determine the formation and evolution of crude oil gelatinization structure.

(3) Due to the large temperature difference between the inside and outside of the vault tank, the cold oil located between the vault tank wall and the top of the vault tank sank and convection increased during the initial temperature drop, and the cold oil was deposited at the bottom of the vault tank, causing the oil temperature at the bottom of the vault tank to drop. In addition, the gelatinization structure appear in the region surrounded by the base wall and sidewall of the vault tank. The hot oil part in the vault tank is mainly concentrated on the upper part, which makes the convection phenomenon mainly concentrated on the hot oil part. As the temperature drops, the cold oil part gradually expands. With the reduction of the hot oil part, the convection in the vault tank weakens, and the gelatinization structure gradually develops along the vault tank wall and the vault tank bottom.

(4) At the initial stage of temperature drop, the flow in the vault tank gradually increases and the upper and middle parts of the vault tank are significant. The convection of the oil near the wall of the vault tank was more intense. As the temperature drop progresses, the oil viscosity increases and the convection weakens. This phenomenon was mainly concentrated in the bottom of the vault tank. With the further decrease of oil temperature, the oil in the vault tank gradually loses its fluidity, and the complete gelatinization layer is formed at the bottom of the vault tank first, and then the gelatinization shell structure is formed at the top, the wall and the bottom of the vault tank.

(5) In the initial stage of temperature drop, the oil temperature of the vault tank center is higher than that of the vault tank top and the vault tank bottom, and the oil temperature of the vault tank bottom is lower than that of the vault tank top. With the progress of temperature drop, the oil temperature in all parts of the vault tank dropped and the temperature transition

part gradually thickened. At the end of the temperature drop, the transition part and the high temperature part gradually merged, and the temperature distribution was uniform and significantly higher than the vault tank top and vault tank bottom part. For different radial positions, the closer to the vault tank wall, the lower the temperature in the cryogenic part at the bottom of the vault tank and the greater the coverage of the cryogenic part.

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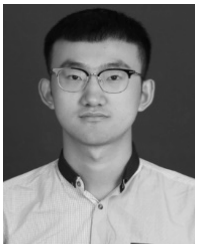

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