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Research on coupled characteristics of heat transfer and flow in the oil static storage process under periodic boundary conditions

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ABSTRACT

With the increasing demand for oil storage, storage tanks are developing towards large-scale tanks better adaptability to extreme working conditions. The variation law of the oil temperature field and the flow field inside the tank should be accurately understood to guarantee safe and economical operation of an oil depot. Aimed at understanding the periodic variation in the ambient environment of the tank's location and the physical properties of the crude oil, the theoretical model of unsteady heat transfer flow in a large floating roof tank was established by using the relative heat transfer theory in this paper. The numerical solution technique for the crude oil temperature field and the flow field was studied. This paper thoroughly analyzed the effect of heat transfer and flow coupling characteristics on the tank static storage process under the influences of the atmospheric temperature, solar radiation, etc. The results show that according to the variation law of the temperature field, the static storage cooling process was divided into a partial rapid cooling stage, overall rapid cooling stage, condensate reservoir growth stage and overall low-speed cooling stage. The heating process was divided into a partial low-speed heating stage and partial rapid heating stage. The solar radiation has a great influence on the temperature fluctuation, and the atmospheric temperature has a great influence on the rate of temperature decrease. The results can provide theoretical support for optimizing the design of the storage process and managing the manufacturing of a large floating roof tank.

0. Introduction

The crude oil reserves in China totalled33.25 million tons in 2016. However, the static storage capacity was only 36 days, which is far below the safety standard of 90 days set by the International Energy Agency and well below the 172 days of the existing average level for other net import member countries [1–4]. Therefore, in China, it is urgent and imperative to accelerate the construction of oil reserves on a large scale by seizing the current favourable opportunity of the low oil prices in the world. With the increasing demand for strategic crude oil reserves in China, the large floating roof tank has become the first choice of large-scale oil storage facilities because of its technical and economic advantages [5]. When the oil temperature is lower than the wax precipitation point in the production operation, an oil solidification layer with a certain thickness and strength can be formed on the inner edge, surrounded by the tank top, tank wall and tank bottom. Some serious phenomena, such as oil solidification in the tank, may occur. Therefore, to ensure the safe and economic operation of an oil depot, the change law of the in-tank oil temperature field and the flow field must be accurately understood [6,7].

Numerical simulation is the main method to study the change law of the temperature field and the flow field in a tank. Cottor [8,9] numerically solved the control differential equations of the vorticity flow function in the natural convection temperature decrease of crude oil using the finite volume method. The flow pattern and heat transfer characteristics in the transient natural convection heat transfer process were obtained, and a simplified calculation model of the temperature decrease was given. Rejane [10,11] performed layer analysis in the small-volume tank, of which the top and bottom act as insulation for hot oil. The temperature field and velocity field during the crude oil temperature decrease in the tank were obtained by estimating the Prandtl and Rayleigh numbers and using the finite volume method for the calculations. Svetlana et al. [12] established a mathematical model of a fuel oil tank that used the tank bottom as a heat source and stored incompressible viscous fluid in the tank. The unsteady Navier-Stokes equation, the energy equation and the heat conduction equation in the initial and boundary conditions were solved. Liang et al. [13] used FLUENT software to study the oil temperature

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Nomenclature

α	heat transfer coefficient, W/(m^2·K)
λ	the heat conductivity coefficient, W/(m^2·K)
Q	heat flux of solar radiation absorbed, W/m^2
ρ	the density of crude oil, kg/m^3
μ	the viscosity of crude oil, Pa·s
c	the specific heat of crude oil, J/(kg·°C)
u	transverse flow velocity of oil, m/s
v	longitudinal flow velocity of oil, m/s
τ	heat transfer time of the unsteady state, s
t	temperature, °C
P	hydrostatic pressure of oil, Pa
q	heat flux lost to the environment, W/m^2
Φ	total heat flux per unit area of the tank, W/m^2
K	total heat transfer coefficient, W/(m^2·K)
I	solar constant, W/m^2
P	atmospheric transparency coefficient, nondimensional
θ	the zenith angle of the sun at noon, °
σ	coefficient related to the day length, nondimensional
m	coefficient related to the atmospheric quality, nondimensional
ε	emissivity of the tank float plate, nondimensional
F	the area of the tank, m^2

Subscripts

1	natural convection
2	forced convection
3	radiation
tf	tank roof
tw	tank wall
tb	tank bottom
en	environment
ex	external
in	internal

at different positions in the central section of the tank to obtain the temperature distribution law in the process of the temperature decrease in the tank. Zhao [14] calculated the distribution of the temperature field in a crude oil tank based on the finite element method. The factors of boundary conditions, storage tank structure and external environment that influence the crude oil heat transfer process were analyzed. Li et al. [15,16] developed a two-dimensional model of a large floating roof tank by analysing the elements that impact the inner or outer temperature of the floating roof tank. Additionally, they developed a program to predict the temperature field, of which the floating area, oil area, soil area, tank wall and insulation layer were solved in a coupled manner using the SIMPLE algorithm.

Previous studies on the heat transfer and the flow coupling characteristics in the oil static storage process have usually adopted the empirical value method when the ambient temperature, solar radiation, and other environmental conditions were set; each of these values is often regarded as a fixed value. The actual situations have been over-simplified, resulting in inaccurate results. Therefore, according to the physical characteristics of static storage in a large floating roof tank, under the comprehensive consideration factors, such as ambient temperature, solar radiation intensity and oil physical parameters, this study established a theoretical model of static storage of oil in a large floating roof tank based on the continuity equation, the momentum equation and the corresponding flow equations. The proposed model revealed the mechanism by which the periodic boundary conditions influence the heat transfer and flow coupling characteristics of the oil static storage process, providing important theoretical support for the production management of an oil depot.

1. Theoretical model of floating roof tank static storage process

The oil temperature in the floating roof tank is mainly determined by the periodic variation in atmospheric temperature and the solar radiation heat absorbed by the tank boundary in contact with the oil. The solar radiation transfers heat to the oil through the atmosphere, the outer wall and the inner wall of the oil tank. As a result, a greater difference between the oil temperature and the air temperature arises. Thus, oil near the tank boundary dissipates heat to the outside through the natural convection with the inner wall, heat conduction of the tank wall, forced convection with the ambient environment and radiation [17]. The physical model is shown in Fig. 1.

To conveniently study the coupling characteristics of heat transfer and flow in the crude oil tank, reasonable simplifications and assumptions made are as follows. After investigating the oil depot, the wax thickness of the tank wall is generally between 0 and 10 mm under normal operating conditions. The total heat transfer of the waxy crude oil accounts for only 0.11–0.15%; thus, the phase transition process of internal wax precipitation in the oil can be ignored. Considering that the thermal conductivity of the oil in the tank is small and the change in the heat flow in the inner area of the tank occurs slowly, the initial temperature can be assumed to be uniform. Furthermore, the tank is an axisymmetric cylinder, and for the static storage process, the ranges of variation in the circumferential temperature and the velocity are small. Ignoring these effects, the floating roof tank can be simplified according to an axisymmetric geometry. Thus, the mathematical model of the crude oil static storage process is established under the overall considered factors, such as the ambient temperature, the solar radiation intensity and the physical parameters of the oil.

1.1. Crude oil variation physical property parameters

With the decrease in the crude oil temperature, both the density and the heat conductivity coefficient gradually increased, each showing a linear relationship with oil temperature. The viscosity variation law can be expressed approximately by the power-law equation. The value increases sharply when the temperature is lower than the anomalistic point. The heat absorption capacity increases first and then decreases. The specific formulas are shown as follows:

(1) The crude oil density:

$$\rho = \rho_{20}[1 - 0.00062(t_{oil} - 20)] \tag{1}$$

where ρ_{20} is the density of 20 °C crude oil, kg·m^{-3}; and t_{oil} is the crude oil temperature, °C;

(2) The crude oil heat conductivity coefficient:

$$\lambda = \frac{117.5}{\rho_{20}}(1 - 0.00054 t_{oil}) \tag{2}$$

(3) The crude oil viscosity:

$$\mu = e^{\wedge}(-28.8 + 8904.4/(t_{oil} + 273.15)) \tag{3}$$

(4) The crude oil heat absorption capacity: