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Research on heat transfer characteristic for hot oil spraying heating process in crude oil tank

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ABSTRACT

The finite volume method and standard $k-\varepsilon$ turbulence model are used to numerically investigate the heat transfer features of crude oil inside the floating roof tank under the hot oil spraying heating mode. The results indicate that this heat transfer process has the essential features of the thermal buoyancy jet flow. The jet flow is divided into the strong buoyancy, weak buoyancy and common buoyancy process according to Froude number of the jet flow. Bigger Froude number of the jet flow indicates stronger heat exchange strength and more uniform distribution of oil temperature. Smaller Froude number indicates stronger buoyancy, weaker heat exchange strength and more obvious hierarchical distribution feature of the oil temperature inside the tank. Two indices (efficiency and uniformity) are introduced and examined which could be of practical usage. According to the simulated result, higher nozzle speed and proper spraying temperature which results in a lager Froude number can achieve better heating effect by taking two previous indices as evaluation criterion. For the practical engineering usage, the spraying temperature and nozzle speed should be adjusted synchronously based on Froude number.

1. Introduction

In the northeast of china, the air temperature in winter can reduced to −30 °C which is much lower than the condensation point of crude oil in that region, leading the safety storage of oil be more difficult. In order to increase the fluidity of oil, keeping it at a high temperature by heating is the most common method. Comparing to the traditional heating mode of heating tube system, the hot oil spraying heating mode has a higher heat exchange efficiency and is extensively applied in the crude oil tank in recent years. For the hot oil spraying heating mode, the oil in the tank becomes the heat transfer media. As the general case, some oil is extracted from the tank and heated to a higher temperature in the heat exchanger. After that, the heated oil which is called hot oil will be pumped back to the tank and be sprayed by the nozzle to be mixed with the cold oil inside the tank. By the mixture process, the temperature of cold oil in the tank will be increased. In the tank, the nozzle and heating tube which is used to transform the hot oil become the main structure of this heating mode. Similar heating technologies are extensively applied in the heat supply system [1,2], but in essence, they belong to application of the jet flow technologies in the heat transfer field. Now the research references on this heating modes are relative limited, but research references on the jet flow based on the buoyancy formed by the heat spreading are plentiful. The early researchers include Jirka [3, 4], Lee [5] and Balasubramaninan [6]. They mainly got the essential features of the phenomena such as

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Nomenclature

c_p	specific heat of crude oil, J/kg·°C
D_j	nozzle diameter, m
H_j	nozzle depth, m
p^*	static pressure, $p^* = p + 2/3\rho k$
$T(x, y, z)$	oil temperature, °C
T_0	initial oil temperature inside the tank, °C
T_j	spraying temperature, °C
T_{bt}	temperature at the top wall, °C
T_{bb}	temperature at the bottom wall, °C
T_{bs}	temperature at the symmetry section, °C
T_{ave}	volume weighted average temperature in tank, °C
T_{ave1}	average temperature in region 1, °C
T_{ave2}	average temperature in region 2, °C
T_{ave3}	average temperature in region 3, °C
T_{ave4}	average temperature in region 4, °C
T_{ave5}	average temperature in region 5, °C
u_i, u_j	mean velocity u, v, w
$u_0(x, y, z)$	initial velocity, m/s
$v_0(x, y, z)$	initial velocity, m/s
$w_0(x, y, z)$	initial velocity, m/s
v_j	nozzle speed, m/s
x_i	coordinate axis x, y, z

Greek letters

α	thermal diffusion coefficient of crude oil, m^2/s
α_t	turbulence thermal diffusion coefficient of crude oil, m^2/s
ϕ	angle between the nozzle tangent and horizontal direction
η_j	temperature increase efficiency
κ_j	temperature distribution uniformity parameter
λ	heat conductivity of crude oil, W/m·k
μ	kinetic viscosity of crude oil, Pa·s
μ_{eff}	effective viscosity coefficient, $\mu_{eff} = \mu + \mu_t$, $\mu_t = \rho C_\mu k^2/\varepsilon$
ρ_a	density of fluid in the tank, kg/m^3
ρ_j	density of spraying fluid, kg/m^3

Indices/exponents

ave	average
a	oil in the tank
bt	top wall
bb	bottom wall
bs	symmetry section
j	Jet flow
0	initial moment
p	constant pressure

vertical plane buoyancy jet flow and horizontal round buoyancy jet flow via the experimental methods. In recent years, the numerical simulation method is becoming a more effective method to solve these problems. Kuang [7,8] conducted numerical research on the plane vertical buoyancy jet flow by using the finite volume method and corrected $k-\varepsilon$ model. Wenxin [9] and Yuhong [10] deeply studied the stability and mixing features of buoyancy jet flow by using the numerical simulation method based on the hybrid finite analysis. All of above research took the water as the medium and are mainly belonged to the buoyancy jet flow problem under the shallow water environment in the hydrodynamics field. Although rich research achievements were achieved, the thermophysical property of crude oil is very different from that of water. Comparing to water, the viscosity of crude oil is much higher and more sensitive to the temperature. And the specific heat capacity of crude oil is about half of water. For the hot oil spraying heating process, the tank is the implemented place of buoyancy jet flow which is different from that in the existing literature as there is a limited space and greater depth. Even if the essential features are similar, existing research achievements can not be directly applied to the hot oil spraying heating process. As the numerical simulation method can cover different working conditions and get comprehensive data, it is used to investigate the hot oil spraying heating process in the crude oil tank so that the flow and heat transfer features during this heating process will be revealed which comes to be the foundation for adjustment and optimization of this heating mode.

2. Calculation model

2.1. Physical model

The research object is a floating roof oil tank which has a removable roof. So the oil can cling close to the roof. The interior zone with the nozzles and tube are taken as the simulated object. A photograph of the nozzle in the tank is shown in Fig. 1. There is always the same distance between two adjacent nozzles. So the tank can be divided into different parts based on the amount of nozzles. For each part, due to the symmetrical feature of structure, one half of the region where one nozzle occupies is taken as the computational domain. Fig. 2 illustrates the physical model and coordinate system of the computational domain. The height of the tank shown in Fig. 2 is 6 m, the radial length is 14 m. Fig. 3 is a separate sectional sketch which shows the detail of the nozzle structure. The diameter of the nozzle is 40 mm, and the angle between the nozzle and x-direction is 45 degree. As can be seen in Fig. 2, the symmetrical section which passes through the center of the nozzle is on the plane z=0. So the radial direction on the symmetrical section is parallel to the x-coordinate axis, while the axial direction of the tank is parallel to the y-coordinate axis.