Study on characteristics of temperature field in cargo tank during heating of cargo oil

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Abstract: In order to avoid the difficulties of unloading due to natural cooling and solidification of cargo oil in the process of shipping, the cargo oil is heated and insulated. In this paper, based on the heat transfer theory, and the fluid dynamics software FLUENT was used to establish a three-dimensional scale model to simulate the actual heating process of the cargo oil in the oil tank, and the change law of the temperature field of the cargo oil in the oil tank was calculated and analyzed. The results show that the temperature of cargo oil is approximately proportional to the heating time. During the heating process of the cargo oil, the rise of the temperature of the cargo oil leads to the increase of oil fluidity, and the oil above the heat source flows upward along the bulkhead, resulting in vortexes of different sizes. In the same heating time, the external temperature difference is 40 K, the oil temperature rise difference is 1.5 K. The variation of temperature field in the heating process of cargo oil is of engineering significance to improve heating efficiency, reduce operating cost and reduce environmental pollution.

1. Introduction

Since many cargo oils have high freezing point and high viscosity, in order to avoid solidification of cargo oils due to natural cooling, it is necessary to heat and keep the cargo oils warm during transportation [1]. In particular, due to the large variation of the temperature gradient of the external environment, there are limitations in heating and insulating the cargo oil. Therefore, adopting an appropriate heating and insulation scheme is of great significance for reducing operating costs and environmental pollution [2]. At present, the heating and insulation of the cargo oil mostly depend on the experience of the crew. Many crew members overheat the cargo oil in order not to delay the voyage. Excessive heating will not only cause the volatilization of light components in oil products and the deterioration of oil quality, but also waste resources and pollute the marine environment, which is contrary to the concept of "green ships" [3].

Jin Zhihui used two-dimensional numerical simulation to restore the heating process of cargo oil, and concluded that the main heat transfer mode in the shipment oil was natural convection [4]. In the design of the cargo oil heating system, Shimizu et al. conducted three-dimensional numerical analysis of unsteady flow and heat transfer to study the influence of the heat loss of the cargo oil tank on the natural convection during the cargo oil heating process. Through numerical analysis, the flow characteristics and oil temperature distribution of cargo oil after heating are obtained [5]. Through numerical simulation, Hu Wenpeng analyzed the heat transfer characteristics of the high viscosity crude
oil in the sunken oil tank during the temperature drop process, and obtained the distribution law of the temperature field and velocity field of the crude oil during the cooling process [6]. Zhu Xiang studied the heating of cargo oil on polar oil tanker, and obtained the change law of heat flux on different wall surfaces. Heat loss was reduced by optimizing the structure of oil tanker, adding thermal insulation layer and baffle and other measures to achieve energy saving effect [2]. In view of the problems of low thermal efficiency and high total oil consumption in the traditional steam heating coil heating method, Zhang Jiakuo proposed a new composite heating method which is mainly composed of steam heating coil and supplemented by microwave heating. It is concluded that the combined heating method has certain energy-saving effect compared with the single heating coil [7]. Yang Yuan, based on the variation characteristics of oil temperature rise in the process of oil heating and insulation at normal temperature, studied the variation characteristics of oil temperature rise in the process of oil insulation at low temperature. By comparing the initial time of convective heat transfer stage and the difference of temperature field inhomogeneity in the oil temperature rise process under different working conditions, the oil insulation process under low temperature environment was explored from the stage difference and regional difference [8]. Because the numerical calculation of the thermal conductivity process of crude oil is too simple, there is a big deviation between the conclusion and the actual situation. In this paper, the three-dimensional numerical model is used to reduce the heating process of cargo oil in the cargo tank, and the viscosity and temperature variation characteristics of oil during the heating process are considered. According to the different external environment, the variation characteristics of oil temperature field are analyzed to improve the heating efficiency of cargo oil and reduce energy consumption, and different heating schemes are provided under different external environment temperatures.

2. Model establishment

2.1 The physical model

The side tank of Very Large Crude Carrier (VLCC) was selected as the research object, and the tank length of 20 m, width of 22 m, depth of 30 m was simplified as a cuboid. The scale model was built according to the ratio of 1:40. The scale model was a double-shell model tank with length of 0.5 m, width of 0.55 m, height of 0.75 m and volume of 206 L. The heating coil was reduced in the same proportion, the diameter of the heating coil was 0.02 m and the length was 0.5 m, and it was arranged at the position 0.02 m away from the bottom. See Figure 1.
2.2 Mathematical model
In the heating process of cargo oil, the governing equations mainly include continuity equation, momentum equation and energy equation. When the temperature of oil increases, the density of cargo oil will change to some degree. Boussinesq equation is mainly used.

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = S_m$$

Where $\rho$ is fluid density, kg/m$^3$; $T$ is time, s; $u_i$ is the absolute velocity component, m/s; $S_m$ is a custom source phase, where it is 0.

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i} + \rho g_i + F_i$$

Where, $P$ stands for static pressure, Pa; $\tau_{ij}$ is the stress tensor; $\rho g_i$ is the gravitational volume force on fluid particle $i$, N; $F_i$ is the external volume force, N, exerted by the fluid particle $i$.

$$\frac{\partial (\rho E)}{\partial t} + \frac{\partial}{\partial x_i} (u_i (\rho E + \rho)) = \frac{\partial}{\partial x_i} (k_{eff} \frac{\partial T}{\partial x_i} - \sum_j h_j J_{ij} + u_j (\tau_{ij})_{eff}) + S_h$$

Where, $E$ is the total energy of the fluid group, J/kg; including the sum of internal energy, kinetic energy and potential energy. $h$ is the stew, J/kg; and $h_j$ is the diffusion flow rate of component j; $k_{eff}$ is the effective heat conduction coefficient, W/m·K; $S_h$ is the volume heat source phase, which is assumed to be 0.

$$(\rho - \rho_0)g \approx -\rho_0 \beta (T - T_0)g$$

Where, $\rho$ fluid density, kg/m$^3$; $\rho_0$ is the density of the fluid at temperature $T_0$; $\beta$ is the volume expansion coefficient, 1/K; $G$ is the acceleration of gravity, N/kg.

3. The numerical simulation

3.1 Model meshing
Before numerical simulation, it is necessary to mesh the model. The basic principle of numerical simulation calculation is to discretely divide the computing domain into multiple control bodies, and then calculate each control body iteratively by eq. (1)-(3) to get the numerical solution. In the scale model, the calculation domain is divided into three parts: the external ballast tank part, the inert gas part in the upper part of the cargo tank and the cargo oil part in the middle. The heating coil belongs to the irregular computing domain, so the unstructured mesh is used near the heating coil. Moreover, this area adopts encryption processing. Since the temperature near the heating coil rises sharply and the change gradient is large, the grid encryption processing can better present the temperature rise near the heating coil. FIG. 2 shows the three-dimensional meshing diagram of the cargo tank.
3.2 Numerical experimental setup
According to literature [2], parameters in the 3D model were set accordingly. Laminar flow model was adopted for the viscous model, uncoupled solver was used for the solution process, and the multinomial flow model was VOF model with the number of terms of 4. Because the process of numerical calculation involves transient problems, the computational domain needs to discretely perform numerical iteration in space and time. The PISO algorithm is used to calculate the three-dimensional transient oil heating problem, and the time discrete scheme adopts the first order implicit scheme.

The boundary conditions and initial conditions of the computational domain are set. Due to the complex convective heat transfer between the external air and the cargo bulkhead, in order to simplify the heat transfer process, the outer wall of the oil tank was set as the heat source surface with constant temperature at 293 K, the bulkhead material was steel plate, and the thermal conductivity was 48 W/(m·k). The initial temperature of inert gas and ballast air and cargo oil is 306.15 K. The loading rate of oil tank is 80%, the density of cargo oil is 860 kg/m³, the specific heat capacity is 1940 J/kg·K, and the thermal conductivity is 0.136 W/m·k. The iteration time step length is 0.01s, and the time step number is 100000.

In order to ensure that the heating process in numerical simulation is consistent with the actual heating process, an experimental lubricating oil with similar viscosity variation characteristics is selected as the experimental oil according to the similarity criterion Grashev number (Gr). The following table shows the thermophysical properties of a lubricating oil.

| Temperature/K | Density/kg·m⁻³ | Specific heat capacity/J·kg⁻¹·K⁻¹ | Coefficient of thermal conductivity/W·m⁻¹·K⁻¹ |
|---------------|----------------|-----------------------------------|---------------------------------------------|
| 306.15        | 860            | 1940                              | 0.136                                       |

4. Results and Analysis
4.1 Analysis of heating results of oil products
In the model experiment, the oil is expected to be heated to about 310 K~315 K, and three temperature monitoring points at 0.1m, 0.25 m and 0.4 m above the heating coil are selected. FIG. 3 shows the curve of the average oil temperature changing with time when the oil is heated for 1000 s under different external environmental temperatures. In the two cases, the average oil temperature reaches 313 K and 311.5 K respectively. Under the condition of the same heating time, the temperature of the cargo oil in the low temperature environment is reduced by 1.5 K compared with that in the normal temperature environment, which indicates that the lower the external environment temperature is, the slower the temperature rise of the cargo oil.

(a)The normal temperature environment \(T=293.15\) K (left)
4.2 Study on variation characteristics of temperature field

FIG. 4 shows the temperature cloud map at Z=0.25 m section in the cargo tank at 293.15 K ambient temperature. The velocity in the positive direction of Y axis is positive. When heated to 100 s, the oil above the heat source starts to heat up, and the temperature rise of the oil in the middle part is more obvious than that on both sides, while there is no obvious temperature rise in other areas. At this time, the oil temperature in the upper part of the heat source increases to 307 K. When the oil is heated to 200 s, the hotter oil begins to flow upward along the bulkhead. When heated to 300 s, the upward flow trend of oil with higher temperature is more obvious, while the oil with lower temperature begins to flow downward due to gravity, which slowly generates a vortex. When heated to 500 s, the oil temperature in the upper part of the heat source is obvious, reaching 313 K. The rise of temperature leads to the decrease of oil viscosity and further enhancement of fluidity. Vortices are constantly generated in the cargo compartment, and thermal convection gradually occurs in the middle part of the oil. When it is heated to 900 s, the oil temperature in the cargo hold rises obviously. The cargo oil continues to flow upward along the right side wall, and there is still a large vortex on the right side.

FIG. 5 shows that the outer wall surface (right wall surface and bottom surface) of the oil tank is set as a constant heat source surface, and the temperature is set to 253.15 K to imitate the low temperature outside. Has been heated to 200 s, when cargo is slowly upward trend, to the 300 s, with the high temperature of cargo oil upward mobility, low temperature of the cargo oil flow down, central tank began to slow the emergence of two different scale vortex, but because of the low temperature environment has a certain influence on the rise of temperature of the cargo, until the 500 s, The temperature of cargo oil on the right side in the cargo hold is lower than that on the left side, and the cargo oil begins to flow upward along the left side wall, thus forming a large vortex on the right side of the cargo hold.

5. Conclusion

By using 3D numerical simulation and numerical experiment method to study the temperature rise characteristics of cargo oil in the process of heating and insulation, the change rule between the
temperature rise of cargo oil and heating time is obtained, that is, the temperature rise of cargo oil is approximately proportional to the heating time.

According to the analysis of the temperature nephogram of oil in different heating stages, it is found that in the early heating stage, the temperature of oil increases obviously only in the upper part of the heat source. As the heating progresses, the oil temperature above the heat source continues to rise, which reduces the oil viscosity and enhances the fluidity. The cargo oil with higher temperature at the bottom flows upward along the bulkhead, while the cargo oil with lower temperature at the top flows downward. Therefore, vortexes of different scales are generated in the flow process of oil, and the temperature of oil in the whole region generally increases and there is an obvious temperature gradient.

According to the different ambient temperature, it can be concluded that under the condition of the same heating time, the lower the ambient temperature, the greater the influence on the temperature rise of the cargo oil, the slower the temperature rise of the cargo oil.

The results are of great significance for understanding the heat transfer mechanism of cargo oil, accurately controlling the heating process of high viscosity cargo oil and reducing energy consumption.

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