Numerical Study on Heating Process of High Viscosity Crude Oil in Oil Tank of Sunken Ship

Yang Shuai¹, Wu Wen-feng¹, Liu Jia², Chen Yong-yan¹, Wang Xu-xiu¹

¹School of Marine and Transportation Engineering, Zhejiang Ocean University, Zhoushan, Zhejiang 316022,
²Ministry of Transport, Institute of Water Transport Science, 100736,
liujia@wti.ac.cn

Abstract. This article assumes that the crude oil in the oil tank of the sunken ship is completely solidified, has high viscosity, and loses fluidity before heating. Based on ANSYS software, a three-dimensional numerical model of the sunken oil tank was constructed, and the numerical study of the heating process of high-viscosity crude oil in the sunken oil tank was carried out. According to the theory of heat transfer, the changes in the solid-liquid interface and the flow characteristics of the oil during the heating process of high-viscosity crude oil are analyzed to obtain the heat transfer characteristics during the heating process. Studies have shown that the heat transfer method at the initial stage of heating is mainly heat conduction, as the highly viscous crude oil continues to melt, the influence of natural convection gradually strengthens. This research can provide relevant theoretical basis for the underwater oil pumping work of salvaging sunken ships.

1. Introduction
Sunken ships will affect the safety of ships daily maritime navigation, therefore, they need to be salvaged. In order to prevent marine pollution caused by oil leakage during the salvage of the sunken ship, it is necessary to conduct underwater oil pumping before salvaging the sunken ship. Due to the different quality of all the oil in the sunken ship, there are oils with high freezing point and viscosity, the oil must be heated before salvaging to ensure that the oil in the sunken ship oil tank can be smoothly transferred out [1]. The oil pumping and heating work of the oil tanks of the submarine sunken ship is currently carried out mostly based on experience. Usually, heating pipes are arranged in the cabins and the pipes are steamed to heat the oil in the cabins.

Kato et al. studied the convective heat transfer of high-viscosity crude oil during the sloshing process by using two-dimensional numerical values based on the sloshing situation of the actual ship [2]. Jin Zhihui conducted numerical experiments on the flow field of crude oil heating process, and verified the simulation results with real ship data, and obtained the conclusion that the heat exchange between cargo oil is mainly through natural convection [3]. Hu Wenpeng studied the cooling process of the high-viscosity crude oil in the oil tank of the sunken ship, and obtained the heat transfer characteristics of the crude oil during the temperature drop [4]. Zhou Jiahai used numerical simulation experiments to obtain the optimal layout of the coils with the same steam power and different positions, and obtained the proportional relationship between oil temperature and heating time [5]. Through the establishment of a full-scale numerical model, Zhu Xiang focused on the study of the influence mechanism of the low temperature environment on the heat transfer characteristics of the cargo oil heating process under the
sloshing effect [6,7]. Costa et al. used scale model experiments to study the heat transfer characteristics of high-viscosity cargo oil within the region [8-10].

Based on the above research, this paper studies the heating process of high-viscosity crude oil in the oil tank of the sunken ship, analyzes the solid-liquid interface change and velocity vector distribution of the crude oil during the heating process through post-processing, and discusses the heat transfer characteristics of the heating process, it can provide relevant theoretical basis for the underwater pumping work of the sunken ship.

2. Model establishment

2.1. Mathematical model construction

During the heating process of high-viscosity crude oil, the required governing equations mainly include continuity equation, momentum equation and energy equation. When the oil temperature increases, its density will change slightly. The Boussinesq model is mainly used to obtain a better convergence rate.

Mass conservation equation (continuity equation):

\[ \frac{\partial \rho}{\partial t} + \nabla (\rho \vec{v}) = 0 \]  \hspace{1cm} (1)

In the formula, \( \rho \) is the fluid density, \( \vec{v} \) is the fluid velocity kg/m\(^3\); m/s; \( t \) is the time, s.

Conservation of momentum:

\[ S = \frac{(1-\varepsilon)^2}{(\rho^2 + \varepsilon)} A_{mush}(\vec{v} - \vec{v}_p) \]  \hspace{1cm} (2)

In the formula, \( \beta \) is the liquid phase ratio; \( \varepsilon \) is a number less than 0.001 to prevent the denominator of the formula from being zero; \( A_{mush} \) is the continuous number of the fuzzy area; \( \vec{v}_p \) is the solid velocity (also called the pulling speed) generated by the solidified material being pulled out of the area, m/s.

Conservation of energy:

\[ \frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot (k \nabla T) + \mathcal{S} \]  \hspace{1cm} (3)

In the formula, \( H \) is the enthalpy energy, J; \( \rho \) is the fluid density, kg/m\(^3\); \( \vec{v} \) is the fluid velocity, m/s; \( S \) is the source phase.

Boussinesq equation:

\[ (\rho - \rho_0)g \approx -\rho_0 \beta(T - T_0)g \]  \hspace{1cm} (4)

In the formula, \( \rho \) is the fluid density, kg/m\(^3\); \( g \) is the acceleration due to gravity, m/s\(^2\); \( \rho_0 \) is the fluid density at \( T_0 \), kg/m\(^3\); \( \beta \) is the volume expansion coefficient of the fluid, 1/K.

2.2. Construction of Numerical Model

The actual cargo oil heating process has a variety of heat exchange forms that are very complicated. In order to simplify the heat exchange process, the following assumptions are made, (1) It is assumed that the oil tank is filled with high-viscosity solid crude oil before heating, and there is no sea water or air in the tank; (2) Oil The crude oil in the tank is regarded as a homogeneous and constant substance, and the temperature of the crude oil in the tank is the same and completely solidified at the initial heating stage; (3) The temperature of the outer wall of the heating pipe is constant.

In this paper, a side tank of an oil tanker is taken as the research object, based on the principle of geometric similarity, the side tank with a length of 22 m, a width of 20 m, and a cabin depth of 30 m is simplified to a model cabin with a length of 0.55 m, a width of 0.5 m and a height of 0.75 m according to the scale ratio of 40:1.

The heating source is a circular pipe with a distance of 0.1 m from the bottom and a radius of 0.02 m. The specific geometric parameters are shown in Figure 1.
2.3. Experimental parameter setting
The ambient temperature is set to a constant of 283K, the wall temperature of the heat source is set to a constant of 400K, the reference pressure is selected as the software default value, gravity is turned on, flow is set to laminar flow, and the solidification/melting model is turned on. The physical parameters of steel plate and crude oil are shown in Table 1.

| Table 1. Physical parameters       | Value                          |
|------------------------------------|-------------------------------|
| Physical parameters                |                               |
| Density (kg/m³)                    | 8030                          |
| Steel plate Specific heat Cp (J/kg K) | 502.48                       |
| Thermal Conductivity (W/(m.K))     | 48                            |
| Steel Density (kg/m³)              | 860                           |
| Thermal expansion coefficient β (K⁻¹) | 0.008                        |
| Specific heat Cp (J/kg K)          | 1800                          |
| Crude oil Thermal Conductivity λ (W/(m K)) | 0.15                        |
| Viscosity (kg m⁻¹ s⁻¹)             | 0.03                          |
| Melting temperature (K)            | 303                           |
| Condensation temperature (K)       | 293                           |

3. Numerical results analysis

3.1. Analysis of velocity vector diagram results
In order to describe the phenomenon more intuitively, an enlarged view of the velocity vector of the heating tube at different times is taken.

Fig. 1 Geometric parameters of the model

(a) t=40s

(b) t=200s
At the beginning of heating, only the solid crude oil near the heating tube melts and starts to flow. In the mid-heating period, it can be seen that the high-temperature crude oil moves in the molten state. It first flows along the outer wall of the heating tube from the bottom to the upper part of the heating tube. After reaching the top, it flows upward along the axis of symmetry. In the later stage of heating, high-temperature melting crude oil meets unmelted low-temperature solid crude oil, which releases heat and causes the temperature to drop. Finally, it flows downward along the cold wall surface formed by the solid crude oil, thereby forming a larger circulation area. Since the melting volume is small at the initial heating stage, the flow is slow and the melting rate is slow. As the heating time progresses, the part of the liquid crude oil produced by melting becomes larger and larger, the flow capacity is strengthened, and the melting rate is significantly increased. The flow rate of crude oil in the high-temperature melting state in the upper part of the heating tube is significantly higher than that in the lower part of the heating tube.

3.2. Analysis of the results of the solid-liquid interface

Figure 3 shows the distribution of the solid-liquid interface of crude oil at different times, and the melting area continues to expand under the condition of continuous heating.

At the initial stage of heating, the crude oil near the heating pipe of the oil tank of the sunken ship
is solid, and there is no relative displacement between the various parts. Therefore, the heat transfer method is mainly heat conduction, and the convection heat transfer situation has not yet appeared and can be ignored. It can be seen from the solid-liquid interface in the middle of heating that as the heating process progresses, it is found that the crude oil only begins to melt near the heating tube. After the solid crude oil in other areas is continuously heated, the heat absorption increases, the melting volume continues to expand, and the density decreases. Due to the density of the cold and hot parts of the fluid is different, the hot fluid moves upward due to the buoyancy force, and relative displacement occurs between the parts. The heat mode has changed, from heat conduction to a combination of natural convection and heat conduction. In the later stage of heating, it can be found that the melting area of solid crude oil gradually increases, and the melting area of solid crude oil on the upper part of the heating tube is significantly higher than other areas. It is found through the post-processing combination velocity vector diagram that this is mainly due to the heat transfer method of the solid crude oil above natural convection, the heat transfer method of the solid crude oil below is heat conduction, and the effect of natural convection is obviously stronger than heat conduction.

4. Conclusion
A more realistic three-dimensional numerical model was used to conduct a numerical study on the heating process of the high-viscosity crude oil in the oil tank of the sunken ship, and the heat transfer form of the heating process of the high-viscosity crude oil was obtained. By analyzing the change of the solid-liquid interface and the velocity vector diagram during the oil heating process, and get the main conclusions as follows: In the initial stage of heating, due to the weak flow capacity of the crude oil in the melting state at high temperature and the limited flow area, the effect of convective heat transfer is very weak and can be ignored, and heat conduction is the main heat transfer method. As the heating time progresses, the crude oil around the heat source begins to heat up and melt, the melting area expands, the flow capacity increases, and the influence of natural convection is significantly strengthened, becoming the main heat transfer method for crude oil. The research conclusions of this paper can provide in-depth understanding of the heat transfer mechanism of high-viscosity crude oil, and provide relevant theoretical basis for underwater pumping work for sunken ship salvage.

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