Sloshing effect of back pressure fluctuation of oil filling pipe in oil tank in heavy sea

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Abstract. During the loading operation of the oil tanker, the oil sloshing is caused by the movement of the carrier liquid and the filling of the liquid cargo. The sloshing force acts on the filling pipe and affects the filling process of the tanker. The main aim of this paper is to back pressure fluctuation of oil filling pipe in oil tank. A more reasonable three-dimensional model was established, and the VOF (volume-of-fluid) model was combined to simulated the change of back pressure. This paper firstly compares the sloshing loads caused by tank loading and movement. The results show that the effect of tank loading on the back pressure of the filling pipe is less than the impact of the tank movement. On this basis, the article further studies the sloshing effect of the tank movement. The test simulated different amplitude of tank to compare and analyze the back pressure variation characteristics of the filling. The results of simulation show that during the tank loading operation, the sloshing pressure load becomes larger as the motion period decreases.

1. Introduction

Loading operation of oil tanker is a dangerous process. Especially in the condition of strong wind and wave, the instability factor of oil tank increases, and the filling pipe of oil tank becomes a dangerous part of stress concentration. During the loading operation of oil tankers, the sloshing of oil products is caused by both the movement of the carrier and the filling of liquid cargo. The sloshing force produced by the sloshing force acts on the filling pipe and affects the filling process of the tanker.

The oil tanker has the characteristics of wide width and high loading depth. Under the action of wave force in a certain frequency range, the motion of the ship hull will lead to intense motion of the tank [1,2]. The sloshing load has a significant impact on the structure and movement of the ship hull, and reduces the operational efficiency and safety [3,4]. In recent years, relevant scholars have studied the sloshing problem of oil products in tank of oil tanker [5-9]. But the above research mainly focuses on the influence of liquid sloshing on hull strength, so there are many studies on the bulkhead pressure of tank. This paper studies the dangerous part of tank filling pipe which is concentrated by stress, and discusses the influence of back pressure change on filling safety and efficiency, taking into account the loading safety and efficiency. The effect of liquid sloshing caused by cargo is studied. The superposition effect of tank motion and loading on oil sloshing is studied.

This paper is mainly based on the VOF method, using CFD (computational fluid dynamics) software to study the ship's oil sloshing, using the control variable method and similar criteria [10] to
refine the influence of various factors on the back pressure of the filling pipe, sloshing the liquid. The effect is supplemented. The impact of oil sloshing caused by loading operations on the back pressure of the filling pipe under the external disturbance. The law of field evolution reduces the influence of the back pressure of the oil pipeline and the amplitude of the back pressure fluctuation, which provides a theoretical basis for optimizing the loading operation of the oil tanker and the design of the cargo tank.

2. Model establishment

2.1. Physical Model
In this paper, a typical VLCC tank is taken as a prototype, and the model cabin is established by geometric similarity criterion considering the validation of model test. Because of the complex structure and layout of the tank and the numerous appendages, it is difficult to study the mechanism of filling pressure change in the tank by using physical numerical model. Therefore, this study neglects the structure around the tank and the upper and lower bulkheads, simplifies the tank into a cuboid model, and ignores the bulkhead thickness of the model and the bulkhead deformation during loading process, as shown in Figure 1.

The model was selected as a large rectangular parallelepiped with a length of 0.46mm, a width of 0.4mm, and a height of 0.47mm. The diameter of the filling pipe is 0.012m, and the length of the filling pipe is 0.46m. The position of the hole core (0.55, 0.20, 0.47); The diameter is 0.016 m and the hole center position (0.25, 0.20, 0.47).

![Fig.1 Physical model of cargo tank](image)

2.2. Mathematical model
In the actual tanker loading process, the oil sloshing power form is very complicated, and the following assumptions are made to simplify the oil sloshing process.

1. Assume that the entire fluid is an incompressible viscous fluid;
2. There is a free interface between the two-phase fluid, and the fluid does not lose during the entire sloshing motion;
3. The energy loss caused by temperature changes is not considered.

2.2.1 Control equation

\[
\frac{\partial}{\partial t} (\rho \mathbf{u}) + \frac{\partial}{\partial x_j} (\rho \mathbf{u} \mathbf{u}_j) = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_t}) \frac{\partial \mathbf{u}}{\partial x_j} \right] + G_i + G_b - \rho \mathbf{e} \cdot \mathbf{Y}_u + S_i \tag{1}
\]

\[
\frac{\partial}{\partial t} (\rho) + \frac{\partial}{\partial x_j} (\rho \mathbf{u}_j) = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_t}) \frac{\partial \rho}{\partial x_j} \right] + C_w + \frac{\rho}{k} (G_i + G_b) - C_c \rho \frac{e^2}{k} + S_i \tag{2}
\]

\[
\mu_t = \rho \alpha C' \frac{k^2}{e} \tag{3}
\]
Where, $G_k$ represents the turbulent flow energy produced by the laminar velocity gradient; $G_b$ is the turbulent flow energy generated by buoyancy; $Y_M$ is the fluctuation due to the diffusion of the transition in the compressible turbulent flow; $\sigma_k$ and $\sigma_e$ are the turbulent Prandtl numbers; $S_k$ and $S_e$ are user-defined.

2.2.2 Continuous equation

$$\frac{\partial \rho}{\partial t} + div (\rho \vec{u}) = 0$$

(4)

Where, $\rho$ is the fluid density; $\vec{u}$ is the velocity in three directions ($u$, $v$, $w$).

2.2.3 Momentum equation

$$\frac{\partial (\rho u)}{\partial t} + div (\rho \vec{u} \vec{u}) = \rho \vec{u} \cdot \nabla \mu \cdot \vec{u} - \frac{\partial p}{\partial x} + F_x$$

(5)

$$\frac{\partial (\rho v)}{\partial t} + div (\rho \vec{v} \vec{u}) = \rho \vec{v} \cdot \nabla \mu \cdot \vec{v} - \frac{\partial p}{\partial y} + F_y$$

(6)

$$\frac{\partial (\rho w)}{\partial t} + div (\rho \vec{w} \vec{u}) = \rho \vec{w} \cdot \nabla \mu \cdot \vec{w} - \frac{\partial p}{\partial z} + F_z$$

(7)

Where, $\rho$ is the fluid density; $\mu$ is the dynamic viscosity; $p$ is the fluid pressure; $F_x$, $F_y$ and $F_z$ are the mass forces of the unit mass fluid in the $x$, $y$, and $z$ directions.

3. Numerical model

3.1. Mesh generation

In order to carry out the research on the change characteristics of the back pressure of the filling pipe in the tank during the loading of the tanker, based on the model assumption, the model of the tanker of the sports tanker is constructed. The physical model of the cargo tank of the tanker was modeled and meshed using CFD software. The divided grids are all hexahedral structural grids, and the filling tubes are processed by O-gridBlock to improve the grid quality. The ICEM software was used to establish a numerical model of the tank.

3.2. Numerical solution method and boundary Condition Settings

A turbulence model is used in the viscous model, and the uncoupled solver (pressure-based solver) is used in the solving process, and the VOF model is selected for the multi flow model. PISO algorithm is used to calculate the 3D transient problem. In order to ensure the accuracy and stability of the numerical calculation, the initial momentum and energy using second order upwind.

3.3. Simulation condition

According to the ship's safe operation requirements and the operating experience of the crew in the tanker, the roll angle of the tanker under normal sea conditions is generally about $10^\circ$. Under the harsh conditions, the angle of the tanker cannot exceed $30^\circ$. The numerical test group is designed within the actual oil tank's motion amplitude range to explore the characteristics of the back pressure of the moving tank filling tube during loading, as shown in Table 1.

| Case | motion periods(s) | motion amplitudes(deg) |
|------|-------------------|------------------------|
| 1    | 10                | 5                      |
| 2    | 10                | 10                     |
Considering that there is almost no empty space during the tank loading operation, the 10% H loading condition is taken as the initial height.

4. Results and Analysis

4.1. Effect of tank movement on filling pipe pressure
This section takes the case of the cargo tank of the loading tanker with a movement period of 10 s and a magnitude of 10 deg as an example, and the pressure of the filling tank of the tank is compared with that of the stationary tanker. The back pressure of the filler tube is shown in Figure 2.

![Fig.2 Time histories of back pressure of the filling pipe](image)

It can be seen that during the loading process of the tanker, the oil load produces a small amount of sloshing load, which has little effect on the back pressure of the filling pipe; the movement of the tank affects the back pressure of the filling pipe seriously, indicating the oil generated by the movement of the ship. The product sloshing effect has a significant superposition effect on the change of the back pressure of the filling tube.

4.2. Effect of tank movement cycle on back pressure of filling pipe

![Fig 3 Curve of motion amplitude on the pipe back pressure of the filling pipe](image)

It can be seen that, in the calculated time, with the increase of the motion amplitude, the amplitude of sloshing pressure exerted by the tank motion increases significantly. The motion rigidity increases the sloshing effect caused by tank motion, and the sloshing effect becomes more intense with the increase of the amplitude. The analysis shows that when the motion amplitude is small, the liquid level on both sides of the tank fluctuates to a certain extent, and the fluctuation of the liquid level on both sides is greater than that of the intermediate level; with the increase of the amplitude, the phenomenon is more obvious..

5. Conclusion
In this paper, a series of simulation experiments are carried out by using the VOF method. According to the influence of the sloshing load on the pipe pressure caused by loading, the sloshing load produced during the loading process of the tanker is compared and analyzed. It is verified that the
sloshing caused by the tank movement has obvious superposition effect on the change of back pressure of the filling pipe during the loading process of the tanker.

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