Study on oil film characteristics of disc surface in a disc skimmer

Zhenchao Shi [1, a], Xiao Li [2, b, *], Shilin Li [2, c], Zongming Wang [2, d], Meng Wang [3, e]

[1] Zhejiang Testing & Inspection Institute for Mechanical and Electrical Products Quality Co. Ltd, Hangzhou, 310051, China;

[2] China University of Petroleum (East China), Qingdao, 266580, China;

[3] HIMILE GROUP Co. Ltd, Weifang, 261500, China

[a] shizhenchao@ztme.com.cn, [b] 1271734775@qq.com, [c] 304333492@qq.com,

[d] wzmcc@upc.edu.cn, [e] 1932510137@qq.com

Abstract. The spinning disc is a key component of the disc skimmer, and its oil carrying characteristics directly affect the performance of the oil skimmer. For a long time, the design of disc skimmer mainly relies on experiences and experiments, which limits the upgrading and optimization of disc skimmer. In this paper numerical simulation research on oil film characteristics of disc surface in skimmers was made by the VOF model, and the influence of disc radius, rotational speed, immersion depth, and oil viscosity and density on the surface oil film characteristics of the spinning disc was analyzed. The results show that the oil film thickness increases and then decreases as the radius of the turntable increases. And the deeper the immersion, the higher the oil film coverage on the disc surface. And the larger the rotational speed, the thicker the oil film on the disc surface within a certain range. As the viscosity of the oil increases, the oil film thickness on the disc surface also increases. When the viscosity is less than 30mPa·s, it is difficult to form an oil film on the surface of the spinning disc. The influence of oil density on the thickness of the oil film is relatively small. The research results of this paper have certain guiding significance for the optimization design of disc oil skimmer.

Keywords: Skimmer disc; VOF model; Thickness of oil film; Numerical simulation; Influencing factors.

1. Introduction

With the rapid development of offshore oil production and marine transportation, oil spill accidents occur frequently at sea. If oil spills on the water surface are not dealt with in time, serious harm to the marine ecological environment will be caused[1-2]. The oil spills on the water surface should be recovered as much as possible to reduce the pollution to the water environment[3]. The oil spill disposal methods on the water surface can be divided into physical method, chemical method and microbial method based on their mechanisms. The chemical method will produce secondary pollution, while the microbial method is relatively slow. The physical method can recover the oil spill quickly without secondary pollution[4]. Disc oil skimmer is a kind of oil recovery device based on physical principles, which has the advantages of simple structure, light weight and low moisture content of collected oil. When the disc oil skimmer works, the floating oil was taken away from the water surface by rotation of the disc. Then, the floating oil is guided into the oil storage tank through a scraping device. So it is of great significance to study the characteristics of oil film on the disc surface.

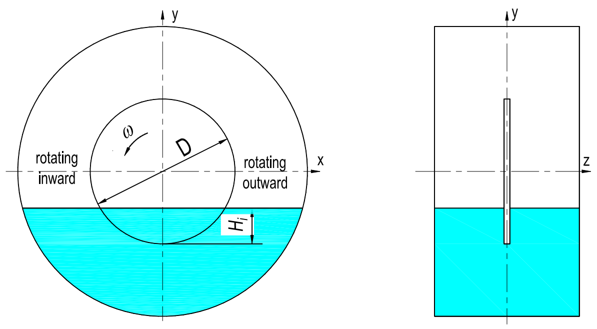
Domestic and foreign scholars have conducted in-depth numerical simulation research on multiphase flow. Zheng Zhifu and Hirt[5-6] used VOF model to simulate gas-liquid two-phase flow, and the law of gas-liquid two-phase flow was obtained and the applicability of VOF model for free interface was verified. Deng Bin and Yang Xiaoyu[7-8] carried out numerical simulation on the liquid film changes of the disk reactor and studied the film thickness characteristics of the disk surface. Yu Jiang[9] et al conducted numerical simulation research on the flow characteristics of liquid film on the surface of biological rotating disc. Sisoev, Afanasiev, Hao Zongrui[10-12] and others have studied the film forming process of the spinning disc, which provides a reference for the simulation method of oil film characteristics of disc surface.

At present, the domestic research on the oil carrying theory of the disc oil skimmer is insufficient, and there are few reports on the experimental research of the disc oil skimmer. For a long time, the design of the disc oil skimmer mainly depends on experiences and experiments, which limits the upgrading and optimization of the disc oil skimmer. In this paper, the oil film characteristics on the surface of spinning disc in disc oil skimmer are studied by numerical simulation, which provides a reference for the optimal design of the disc oil skimmer.

2. Calculation Model

2.1 Geometry and meshing

Assuming that all the liquid that submerges the spinning disc is oil, and the oil is brought out from the liquid level by rotating the disc. In order to simplify the modeling, the oil tank is designed as a cylinder coaxial with the spinning disc. The diameter of the oil tank is twice the diameter of the spinning disc, and the length of the tank is equal to the diameter of the spinning disc, as shown in Fig.1, where, ω is the rotating speed of the disc, and D is the diameter of the spinning disc; H_i is the immersion depth of the disc. The rotation axis of the disc is set as the Z axis. The basic spinning disc has a diameter of 100mm and a thickness of 4mm. and the oil has a viscosity of 1000mPa·s ,a density of 800 kg/m^3, and a surface tension of 0.0072N/m. And the basic rotational speed of the disc is 60 r/min. Use ICEM to mesh the computational domain and because the flow velocity at the edge of the spinning disc has a large gradient, the boundary layer grid of 4 layers at the edge area of the disc were set firstly before the volume grid division was made. The grid division of computational domain is as shown in Fig.2.



(a) front view (b) side view

Fig. 1 Schematic diagram of disc oil skimmer

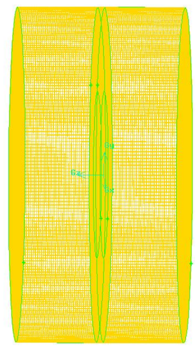


Fig. 2 Grid division

2.2 Governing equations

The fluid flow governing equations include volume fraction equation, mass conservation equation, and momentum conservation equation. In order to simulate the oil film characteristics on the spinning disc surface in disc oil skimmers, the VOF model is employed for multiphase model, and the RNG $\kappa\text{–}\varepsilon$ turbulence model was used for fluid flow.

Volume fraction equation:

$$\frac{\partial \alpha_q}{\partial t} + \overrightarrow{v_q} \cdot \nabla \alpha_q = \frac{S_{\alpha_q}}{\rho_q} + \frac{1}{\rho_q} \sum_{p=1}^{n} (m_{pq} - m_{qp}) \tag{1}$$

$$\sum_{q=1}^{n}\alpha_{\mathrm{q}}=1 \qquad (2)$$

Where α_{q} is the volume fraction of phase q, ρ_{q} is the density of phase q, m_{pq} is the mass transfer from phase p to phase q, and m_{qp} is the mass transfer from phase q to phase p; S_{α_q} is a source item.

Mass conservation equation:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \qquad (3)$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla(\rho\vec{v}\cdot\vec{v})=-\nabla p+\nabla\tau+\vec{F} \qquad (4)$$

Where ρ is the density, t is the time, $\vec{v}$ is velocity vector, p is the pressure, τ is the stress tensor, $\vec{F}$ is the momentum source term.

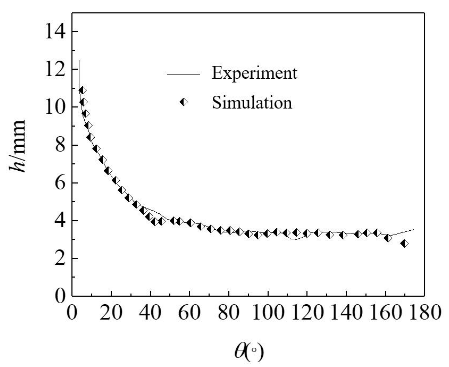
2.3 Boundary conditions

The three surfaces of the spinning disc adopt non slip wall conditions, and the wall of the oil tank is treated as the default wall. And the gas phase is air and the liquid phase is oil. The initial gas-liquid two-phase region is defined before calculation, and the oil phase is defined using the adaptive grid function (Region Adaptation). PISO algorithm is used for transient solution, and second-order upwind scheme is used for solution of momentum equation. Least Squares Cell Based is used for variable difference, and second-order scheme is used for pressure difference, and second-order upwind scheme is used for turbulent kinetic energy and dissipation rate.

2.4 Grid independence and result correctness verification

In order to ensure the accuracy of the numerical simulation, 660 thousand, 860 thousand, 1.16 million and 1.36 million grids were employed respectively for computational domain to verify grid independence of numerical calculation. The simulation results show that when the grid number is greater than 1.16 million, the oil film thickness on the surface of the spinning disc tends to be constant, and the grid number selected for subsequent calculation is 1.16 million.

Afanasiev et al[11] used the FARO three-dimensional rotatable laser scanning measurement system to measure the liquid film thickness profile on the disc surface. The viscosity of silicon solution is 1480mPa·s, and its density is 985kg/m^3. The radius of the disc is 200mm, and the rotating speed of the disc is 90r/min. Using to the same conditions, the liquid film thickness profile with oil phase volume fraction being 0.9 at a radius of 100mm was obtained by numerical simulation, as shown in Fig.3. It can be seen from Fig.3 that the variation curve of liquid film thickness obtained by numerical simulation is in good agreement with the experimental results, which verifies the correctness of the calculation method and numerical model.



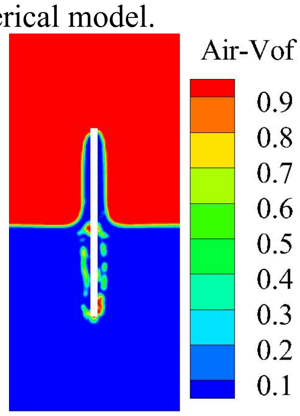


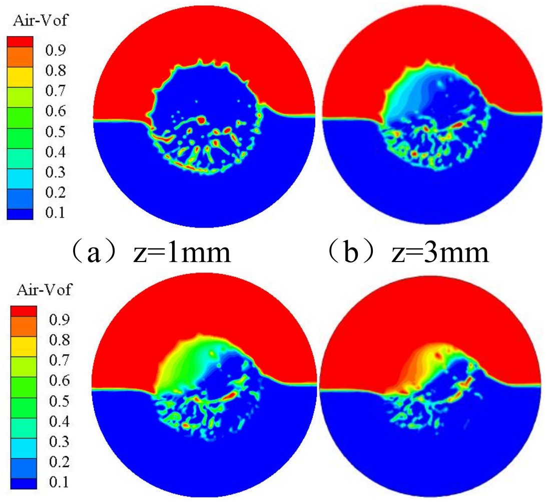
Fig. 3 Experimental liquid film thickness vs simulation results

Fig. 4 Film thickness contours on θ=90°

3. Analysis of Typical Simulation Results

The key to the oil collection for the spinning disc is to form an oil film on the disc surface by adhering the oil through rotating disc. The oil carrying capacity of the disc can be explored by analyzing the oil film thickness distribution and its influencing factors.

When the immersion depth is 50mm, that is half circle disk immersion, during the rotation of the disc, due to the effects of surface tension and viscous force, oil product was dragged upwards along the disc surface, and an oil film on the disc surface was formed. The gas-liquid two-phase distribution of θ=90 ° on the disc side after the disk rotates for two cycles is shown in Fig.4, in which the red part represents air and the blue part represents oil. It can be seen from the Fig.4 that the oil film thickness distribution on both sides of the disc is basically the same. The rotation of the disc will bring the oil away from the free surface of oil and form an oil film on the disc surface. At the same time, the rotation of the disc will also bring some air into the liquid and form bubbles beside the submerged part of the disc.



（a）z=1mm （b）z=3mm

（c）z=4mm （d）z=5mm

Fig. 5 Gas-liquid contours on the spinning disc

Fig.5 shows the contour map of gas-liquid two-phase distribution at different positions from the disc surface after the disc rotates for two cycles. It can be seen from Fig.5 that as the distance from the surface of the spinning disc increases, the binding force of the disc to the liquid film decreases gradually, and the average volume fraction of the oil phase in the section decreases, and the amount of entrained bubbles increases.

4. Analysis of Influencing Factors

4.1 Influence of radial position of disc

The diameter of the spinning disc is 400mm, and its thickness is 10mm. The oil viscosity is 300mPa·s, with the density of 800kg/m^3, and the surface tension is 0.0072N/m. The rotating speed of the disc is 100r/min. The relationship between the radius position of the spinning disc and the film thickness is obtained, as shown in Fig.6.

It can be seen from Fig.6 that with the increase of the radius of the spinning disc, the average film thickness first increases and then decreases. When the radius is 170mm, the average film thickness is the largest, and the film thickness reaches 7.6mm. This is mainly because the oil film on the surface of the spinning disc is subjected to centrifugal force and moves outward, resulting in the thickening of the oil film with the radius increasing. But at the edge of the spinning disc the oil film is thrown away from the spinning disc. Part of oil film away from the disc results in a gradual reduction in the thickness of the oil film within a certain distance from the outer edge.

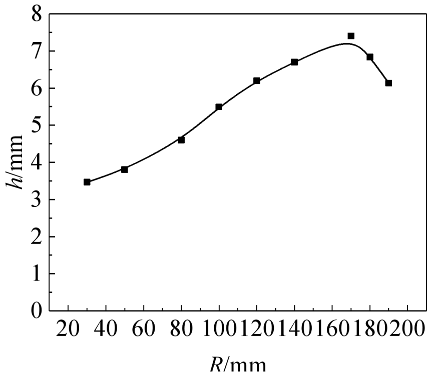


Fig. 6 Radial position of disc vs film thickness

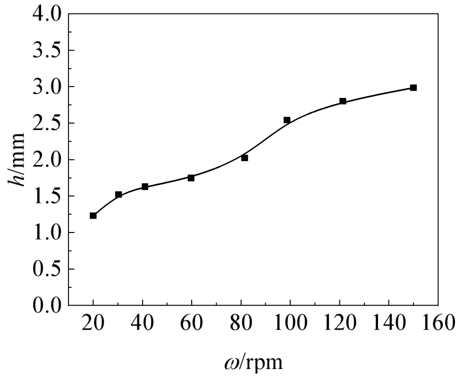


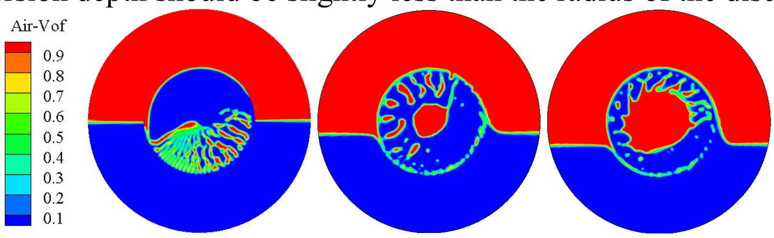
Fig. 7 Rotating speed vs average film thickness

4.2 Influence of rotating speed

Fig.7 is the variation curve of average film thickness under different rotating speeds in the steady state. It can be seen from the curve that the average film thickness on the disc surface increases gradually with the increase of rotating speed, but when the rotating speed is greater than 100r/min, the variation of average film thickness with rotating speed is relatively small. Therefore, considering the detachment effect at the edge, it is better for the working speed of the disc oil skimmer to be lower than 120r/min.

4.3 Influence of immersion depth

The diameter of the spinning disc is 100mm, and the rotating speed of the disc is 100r/min in this case. Contour maps of oil-gas two-phase for different immersion depths of the spinning disc are shown in Fig.8. It can be seen that with the decrease of immersion depth, the oil film coverage on the disc surface continues to decrease. The oil film is limited to the submerged annular area of the spinning disc, and the oil carrying capacity of the spinning disc also decreases with the decrease of immersion depth. The deeper the immersion of the disc, the greater the oil film coverage. When the immersion depth of the disc is equal to the disc radius, the oil film coverage on disc surface is the largest. But in the actual working condition, considering the installation of the oil collection mechanism, the immersion depth should be slightly less than the radius of the disc.



（a）*Hi* =50mm （b）*Hi* =40mm （c）*Hi* =30mm

Fig. 8 Oil film distribution for different immersion depths

4.4 Influence of viscosity

If the disc is immersed in oil, the viscous force of the oil film on the disc surface depends on the viscosity of the oil product. Under the condition of keeping other parameters constant, the oil carrying capacity of the spinning disc was simulated with viscosities of 30mPa·s, 100mPa·s, 300mPa·s, 500mPa·s and 1000mPa·s respectively. Fig.9 shows the variation of liquid film thickness under different viscosities at a radius of 30mm on the spinning disc. It can be seen from

Fig.9 that the oil film thickness increases with the increase of viscosity. When the viscosity is 30mPa·s, the oil film thickness in the roll-off area is very small, and it is smaller in the stable area of oil film. Therefore, when the oil viscosity is less than 30mPa·s, it is difficult to form oil film on the disc surface. Fig.10 shows the effect of viscosity on the average oil film thickness on the surface of the spinning disc. From Fig.10, it can be seen that as the viscosity increases, the average oil film thickness also increases. When the viscosity is greater than 500mPa·s, the increasing trend of oil film thickness slows down.

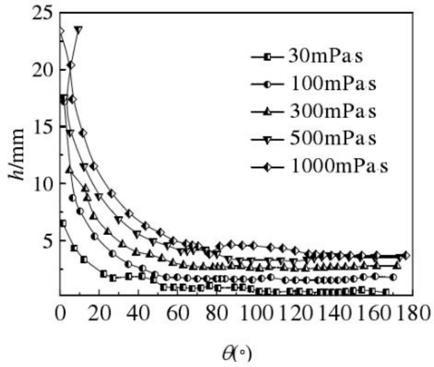


Fig. 9 Oil film thickness under different oil viscosities

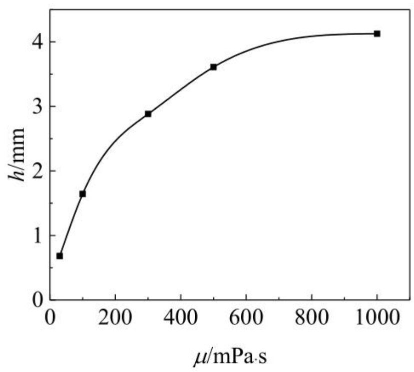


Fig. 10 Average oil film thickness vs oil viscosity

Fig.11 shows the relationship between oil density and average oil film thickness on the surface of the spinning disc. It can be seen that with the increase of density, the oil film thickness gradually decreases. This is mainly because when the density is high, the gravity of the oil film is large, and the viscous force is relatively small, and the oil film on the disc surface falls off under the action of gravity. Then the oil film on the surface of the spinning disc becomes thin, and the oil carrying capacity decreases. Overall, the influence of oil density on oil film thickness is relatively small.

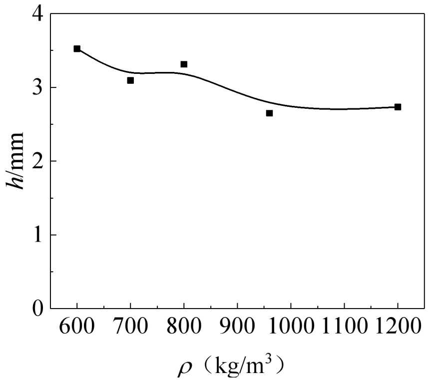


Fig. 11 Oil density vs film thickness

5. Conclusions

Through the study of the characteristics of oil film on the surface of the spinning disc and its influencing factors, the main conclusions drawn are as follows: (1) For a given spinning disc, the oil film thickness first increases and then decreases with the radius position increasing. The average film thickness is the maximum at the radius of 170mm, and the film thickness is 7.6mm here. (2) The higher the rotating speed of the spinning disc, the thicker the oil film on the disc surface. When the rotating speed is greater than 100 r/min, the average film thickness increases less with the increase of rotational speed. Therefore, considering the edge detachment effect, it is better for the working speed of the disc oil skimmer to be lower than 120r/min. (3) As the immersion depth of the spinning disc increases, the oil film coverage area on the disc surface becomes larger, but considering the actual oil collection structure, the immersion depth of the spinning disc should be less than the radius of the spinning disc. (4) With the increase of oil viscosity, the oil film thickness on the disc surface increases obviously. When the viscosity is less than 30mPa·s, it is difficult to form oil film on the surface of the spinning disc. And oil density has little effect on oil film thickness.

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