Numerical Simulation of the Effect of Small-Particle Size Droplet Removal in a Ship Desulfurization Tower Demister

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Abstract. The demisting efficiency of three structure demister and the influence of hook plate on the efficiency of demister were analyzed using fluent software. For a droplet with a particle size of 20μm, when α= 90°, L=20mm, and the inlet speed v=5m/s, the demisting efficiency of the wave plate demister has reached 96.67%. After installing the hook plate, the efficiency of the wave plate demister was significantly increased, the efficiency of the streamline plate demister was more than doubled, and The efficiency increase of the fold line plate demister was small. Finally, the comprehensive analysis showed that the wave plate demister had the highest efficiency and increasing the hook plate could increase the demisting efficiency but at the same time increased the pressure drop.

Introduction

With the rapid development of the global shipping industry, the exhaust gas and particulate matter (PM) produced by ships have gradually become important sources of pollution in coastal areas. The IMO and some countries have stated that the future sulfur and PM emission standards will exceed existing regulatory standards[1,2]. In order to meet increasingly stringent regulatory requirements, wet desulfurization systems have been used more and more widely on ships, but droplets formed after flue gas desulfurization contain polycyclic aromatic hydrocarbons(PAHs), organic carbon (OC) , elemental carbon(EC) and sulfates[3,4], therefore, it is very necessary to remove the droplets formed by wet desulfurization, and the demister as one of the main equipment of the system, has an obvious trapping effect on the droplets after wet desulfurization[5,6].

At present, researches on demisters were mostly focused on desulfurization towers of power plants. Zhichun Sun had carried out numerical simulation on the internal flow field of the desulfurization tower of a 600MW power station. It had been concluded that increasing the number of turns of the demister can significantly improve the efficiency of demisting[7], but too many turns were difficult to meet the special requirements of the ship's space requirements. Yinfei Zheng used CFD simulation and compared with the experimental results. It was found that most droplets were captured when the droplet diameter was larger than 30 μm, and only a few droplets escaped. But it couldn’t effectively solve the small droplets with a particle size smaller than 30 μm[8].

This research was aimed at the special working environment of ship desulfurization tower, and focuses on small droplets with a diameter of 10 – 30 μm. The CFD simulation technology was used to numerically simulate the ship desulfurization tower demister. To solve the problem of removal of fine droplets, providing a reference for the design of the demister of the ship desulfurization tower.

Mathematical Model of Demister

Turbulence Model

Since the gas phase flow state in the demister was turbulent, the k-ε model was widely used in engineering. The turbulent kinetic energy k equation and the dissipation energy ε equation were:
\[
\frac{\partial k}{\partial t} + \nabla \cdot \left( \frac{\mu_k}{\rho} \nabla k \right) = \frac{\partial}{\partial x_i} \left( \mu_k \frac{\partial k}{\partial x_i} \right) + \mu_k \nabla^2 k - \varepsilon
\]  

(1)

\[
\frac{\partial \varepsilon}{\partial t} + \nabla \cdot \left( \frac{\varepsilon}{\rho} \nabla \varepsilon \right) = \frac{\partial}{\partial x_i} \left( \mu_k \frac{\partial \varepsilon}{\partial x_i} \right) + C_1 \frac{\varepsilon}{k} \mu_k - C_2 \frac{\varepsilon^2}{k}
\]  

(2)

where: \( \mu_k \) is the viscosity coefficient of turbulence, \( G \) is the generation rate of turbulence energy.

**Discrete Phase Model**

The internal flow field of the demister was a two-phase flow problem including smoke in the gas phase and droplet particles in the liquid phase. The discrete phase (DPM) model was suitable for very sparse granular phases, and the volume fraction of droplets in the demister was much less than 10\%. Therefore, this paper used the discrete phase model to numerically simulate the two-phase flow in the demister. The discrete phase model could simulate the forces on the discrete phase (liquid droplet phase), thereby establishing a governing equation in Langerange coordinates and analyzing the law of droplet movement.

\[
C_D = \begin{cases} 
\frac{24}{Re} (1 + 1.5 Re^{0.687}) (Re \leq 1000) \\
0.44 (Re > 1000) 
\end{cases}
\]  

(3)

\[V_t = V_0 + at\]

(4)

\[S = V_0t + \frac{1}{2}a(\Delta t)^2\]

(5)

\[
m_p \frac{du_p}{dt} = F_D + F_g
\]

(6)

where: \( m_p \) is the mass of the droplet; \( u_p \) is the velocity of the droplet; \( F_D \) is the drag force of the droplet; \( F_g \) is the gravity of the droplet; \( C_D \) is the drag coefficient; \( Re \) is the number of particles Reynolds.

\[
F_D = \frac{18 \mu}{\rho d_p^2} \frac{C_D Re}{24} (u - u_p)
\]

(7)

\[
Re = \frac{\rho d_p |u - u_p|}{\mu}
\]

(8)

where: \( \rho \) is the density of air; \( u \) is the velocity of gas; \( d_p \) is the diameter of the droplet; \( u_p \) is the density of the droplet.

**Establishment of Physical Model and Numerical Simulation Model of Demister**

**Demister Physical Model**

Due to the normal operation of the demister, the flow field in each channel of the demister was repetitive. Therefore, a single channel was selected to create a two-dimensional geometric model. Figure 1 showed the structure of the wave plate, streamline plate, and broken line plate demister with or without a hook plate. In this calculation, \( \alpha \) was selected from 70 \(^\circ\), 80 \(^\circ\), 90 \(^\circ\), 100 \(^\circ\), 110 \(^\circ\) and 120 \(^\circ\), \( L \) was selected from 20mm, 30mm, 40mm, and 50mm, and the remaining parameters were designed according to the physical models of Hanxiao Liu \([9]\), B. Zamora \([10]\), etc.

Figure 1. Demister structure.
Establishment of Numerical Simulation Model

Meshing and Setting of Boundary Conditions. ICEM CFD was used to divide the grid. All tri method was used to divide the unstructured grid inside the demister. The wall was densified. The grid was imported into fluent 16 for calculation. The inlet was the velocity inlet, the outlet was the pressure outlet, the droplet phase inlet and outlet were escape, the wall was set as capture, and the droplet diameter under different working conditions was set as 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30 μm respectively. The inlet flow rate was set to 3,4,5,6m/s according to the exhaust parameters of 6S35ME-B9.5 marine low speed diesel engine.

Table 1. Diesel engine exhaust steam parameters.

| Parameters          | 25% | 50% | 75% | 100% |
|---------------------|-----|-----|-----|------|
| Exhaust flow rate(㎏/s) | 4.1 | 6.6 | 9.2 | 11.3 |

The inlet velocity of the demister exhaust gas was calculated by the following formula

\[ v = \frac{M}{\rho \pi D^2} \]  
(9)

\[ \rho \approx 1.293 \times \frac{273}{T} \times 1.015 \]  
(10)

where: M is the exhaust flow; D is the diameter of desulfurization tower; \( \rho \) is the density of exhaust gas. The temperature of waste gas after desulfurization is 323K.

Basic Assumptions. There were complex processes of heat, mass transfer and chemical reaction in the flow field of demister. In order to facilitate the calculation, the following reasonable assumptions are made.

1. Air was used instead of flue gas for calculation and it was assumed to be incompressible fluid.
2. Uniform distribution of droplets in the inlet space[11].
3. The velocity of droplets was the same, the interaction between droplets was ignored, and the aggregation and fragmentation of droplets were not considered.
4. Water was used instead of slurry droplets and the droplets were spherical and the effect of droplets on the flow field was ignored.
5. When the droplets contact the wall of the demister, they were considered to be trapped. When they reach the outlet, they were considered to be escaped, and ignoring the secondary entrainment of the slurry.

Analysis of Calculation Results

The Effect of Plate Structure on the Efficiency of Demister

Figure 2 shows the relationship between droplet diameter and demisting efficiency when \( v = 5 \text{m/s} \), \( L=20 \text{mm}, \alpha=90^\circ \). Figure 3 shows the internal droplet velocity streamline. It could be seen from Figure 2 that the demisting efficiency of wave plate demister was higher. For 20 μm droplet, the efficiency of wave plate demister had reached 96.67%, while the efficiency of streamline plate demister and broken line plate demister was 34.29% and 32.86%. Respectively, because the wave plate structure has a larger windward area and the turning angle of the droplet was smaller, the speed of the droplet increases more when it passes through the turning point, resulting in a larger centrifugal force and a larger moving radius, so that the droplet was more likely to collide with the second windward side to increase the demisting efficiency. However, the return area of streamlined and broken plate demisters was larger, the windward area was smaller, and the high-speed air flow after turning was larger in front of the colliding wall, which makes most of the droplets flow out of the demister along the flow field without colliding with the wall.
The Effect of Hook Plate on the Efficiency of Demister

Figure 4 shows the efficiency comparison of three structures of demister after the hook plate was installed. Figure 5 shows the velocity streamline diagram of 12 μm droplet at the inlet velocity \( v=5 \text{m/s} \), \( \alpha=90^\circ \), \( L=20\text{mm} \). It could be seen from Figure 4 that the demisting efficiency increases after the hook plate was installed. For 12 μm diameter droplets, the efficiency of wave plate demister has increased by 85.12%, and the efficiency of streamline plate demister and broken plate demister has increased by 16.39% and 0.8%, respectively, because on the one hand, when the droplets pass through the hook plate, the flow area decreases and the speed increases, which makes the droplets more likely to collide with the wall after turning. On the other hand, the hook plate version The body will also catch some drops. The obvious reason for the increase of wave plate structure was that the return area was smaller and the end of the hook plate was closer to the wall, which increases the effective catching area of the hook plate and reduces the circulating area of the droplets, and then the increase of velocity was larger. After turning, the high-speed droplets will hit the wall earlier and catch. The reason why the efficiency increase of the zigzag demister was not obvious was that the larger reflux area will make the hook plate far away from the droplet flow and weaken the catching effect of the hook plate on the droplet. When the droplet size was larger than 18 μm, the efficiency increases slightly, because the hook plate will reduce the flow area and improve the flow rate, while the larger the particle size is, the greater the inertia force is, which makes the droplet easier to separate from the air flow.
Figure 5. Have hook plate demister internal droplet velocity flow.

**Effect of Installing Hook Plate on Pressure Drop in Demister**

Figure 6 shows the internal pressure nephogram of the demister with three structures at $\alpha=90^\circ$, inlet velocity $v=5\text{m/s}$, $L=20\text{mm}$, with or without hook plate. It could be seen from Figure 6 that the internal pressure drop of the demister increases significantly after the hook plate was installed, mainly because the downstream return area after the hook plate was installed was larger than that without hook plate, and the energy consumption mainly occurs in the return area, so the pressure drop of the demister with hook plate was larger than that without hook plate. The biggest increase of pressure drop of wave plate demister was due to the maximum effective length of hook plate, which leads to the maximum change of internal flow area and the maximum change of return area, which leads to the significant increase of pressure drop.

![Figure 6. Demister internal pressure cloud map.](image)

a. No hook plate  

b. Have hook plate

**The Effect of Turning Angle on the Efficiency of Demister**

Figure 7 shows the relationship between droplet diameter and demisting efficiency of wave plate demister at different turning angles. Figure 8 shows the streamline diagram of droplet velocity at turning angles of 80°, 100° and 120°. Respectively, when the inlet velocity is $v=5\text{m/s}$, the smaller the turning angle is, the higher the trapping efficiency of droplet with small particle size will be, and the demisting efficiency will decrease with the increase of turning angle. For 18 μm particle size The efficiency of the mist demister was 100%, 99.29%, 65.83%, 54.29%, 44.29% and 35.71%. Respectively, the reason was that the larger the turning angle means that the smaller the deflection of the droplet along the direction of the incoming flow, the higher the flow will flow along the flow field instead of hitting the wall after the turning, which makes it more difficult for the droplet to separate from the flow.

![Figure 7. Relationship between droplet diameter and demisting efficiency at different turning angles.](image)
The Effect of Plate Spacing on Demisting Efficiency

Figure 9 shows the relationship between droplet diameter and demisting efficiency under different plate spacing of wave plate demister. Figure 10 shows the streamline diagram of droplet velocity with 18 μm particle size when plate spacing was 20 mm and 40 mm, inlet velocity v=90 m/s, α=90°. It could be seen from figure 9 that the demister efficiency will significantly decrease with the increase of plate spacing. When particle size was 18 μm, the demisting efficiency with 20 mm plate spacing could reach 65.83%, while that between 40 mm plates can reach 65.83% The demisting efficiency of the distance has been reduced to 10.37%. It could be seen from Figure 10 that the increase of plate spacing means the increase of the liquid drop's flowable area, so that most of the high-speed liquid drops after turning will not hit the wall. For the demister with 40mm plate spacing, the high-speed liquid drops after the second turning will not even hit the wall.

Figure 9. Relationship between droplet diameter and demisting efficiency under different plate spacings.

Figure 10. Velocity diagram of internal demister at different plate spacings.

Effect of Inlet Velocity on Demisting Efficiency

Figure 11 shows the relationship between droplet diameter and demisting efficiency at different inlet speeds when α = 20° and L = 20 mm. It can be seen from Figure 11 that the demisting efficiency will
increase with the increase of inlet speed, and the larger the particle size is, the more obvious the rate is. For 14 μm droplet, the demisting efficiency is 9.17%, 10%, 18.33% and 25% respectively, while for 18 μm droplet, the demisting efficiency will increase to 12.5%, 28.33%, 65.83% and 95.83%, the main reason is that with the increase of flow rate, the larger the inertia force on the large-sized droplets increases, the easier it is to be captured and removed by the demister, while the smaller the droplets are more mobile with the airflow, and the less affected by the inertia force, so it is less affected by the flow rate.

Conclusions

In this study, CFD method was used to simulate the demister of marine desulfurization tower, and the conclusions were as follows:

Among the three types of mist demister, wave plate demister has the highest efficiency, which was more effective for the removal of 14-18 μm particles. However, the efficiency of streamline plate demister and broken plate demister was basically the same, which was only different at 26 μm.

The efficiency of the three structure demisters will increase after the hook plate was installed, but the pressure drop will also increase.

The demisting efficiency decreases as the turning angle increases. The smaller the turning angle, the higher the efficiency of trapping small droplets.

With the increase of the plate spacing, the demisting efficiency will decrease, and the efficiency decline is most obvious when the plate spacing is increased from 30mm to 40mm.

The demisting efficiency increases as the inlet speed increases. The larger the particle size, the greater the effect of the inlet speed.

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