Effect of Solid Particles on Cavitation and Lubrication Characteristics of Upstream Pumping Mechanical Seal Liquid Membrane

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Abstract

In order to investigate the effect of solid particles on the cavitation characteristics and lubricating properties of the micro-gap liquid film in Upstream pumping mechanical seals, the Eulerian multiphase flow model was used to simulate the liquid film with different diameter and volume fraction of solid particles to analyze the influence of the particles on the distribution of vacuole, opening force and friction torque of the film under different working conditions. The results showed that the particles have an inhibitory effect on the cavitation, and the cavitation area and the volume fraction of the bubbles were both decreased. The cavitation area increased with the increase of particle diameter, which indicated that the inhibition of cavitation was weakened with the increase of particle diameter. The cavitation area decreased with the increase of the particle volume fraction, and the volume fraction increased the cavitation inhibition effect. The presence of particles improved the opening force of liquid film to a certain extent and increased with the increase of particle volume fraction, but the effect of particle diameter on opening force was different under different rotating speed and different medium pressure. The friction torque did not change obviously with the particle diameter, and decreased only slightly with the increase of the particle volume fraction. In the working condition range, the cavitation degree is not related to the pressure of the medium, but increases with the increase of the rotational speed, and the cavitation area and volume fraction of bubbles were significantly decreased when there were solid particles.

Keywords: Upstream pumping mechanical seal, Particles, Cavitation, Lubrication, Opening force, Friction torque.

1. Introduction

As a new type of hydrodynamic and static contactless mechanical seal[1], the upstream pumping mechanical seal can realize zero leakage or even zero escape of the sealing medium. It has long service life, low operation and maintenance cost, and obvious economic benefit, and has been gradually applied to petrochemical-related fields[2]. In the upstream pumping mechanical seal applications, the media impure and other factors often lead to the end of liquid film mixed with small particles, which easily lead to block the pumping tank and loss of pumping capacity, so that the leakage of sealing and loss of fluid lubrication conditions lead to early sealing failure. Aiming at the problem of multiphase flow in micro-gap of mechanical seal, the main research work of gas-liquid and liquid-solid two-phase flow are studied. In the gas-liquid two-phase flow, Payvar and Salan[3] studied the flow field of the liquid film at the end face of the mechanical seal, and proposed a numerical algorithm which can be used to determine the cavitation boundary of the liquid film. Li J H[4] solved five seal structures and two boundary conditions with MATLAB. Qiu Y. and Khonsari M.M. [5], Hu J B et al. [6] calculated the JFO cavitation boundary for laser processing porous end face and radial straight groove end seal, respectively. Li Z T et al. [7] used the finite control volume method to discretize the control equations, and comprehensively analyze the effects of different amplitudes, wavenumber and taper on cavitation. Hao M M et al.[8-9] studied the cavitation effect of operating parameters on the opening force, liquid film stiffness, leakage and cavitation area changes. Wu Q B et al.[10] studied the cavitation characteristics of upstream pumping mechanical seals, analyzed and compared the different cavitation models and different working conditions of the impact on the opening force, liquid film stiffness, leakage and cavitation area changes; Wang B et al.[11] based on the Antoine formula, the upper reaches of the pumping mechanical seal cavitation thermal effects were studied to analyze the cavitation heat effect on the sealing performance. In the solid-liquid two-phase flow, Zuo M Z et al.[12] simulated the micro-gap solid-liquid two-phase flow of the mechanical seal by using the mixture multiphase flow model, compared and analyzed the flow characteristics and sealing performance.
of the micro-scale liquid film. However, for the liquid-solid two-phase lubrication problem, the cavitation effect is unavoidable and should belong to the gas-liquid-solid three-phase flow problem, which has not been reported.

Therefore, in this paper, the gas-liquid-solid multiphase flow model involving the cavitation and solid particles is established based on the liquid film of the upstream pumping mechanical seal end face. The influence of solid particles on the cavitation and lubrication performance of the mechanical seal of the upstream pumping mechanical seal under the cavitation condition was studied, which provided the theoretical basis for the design of the high performance upstream pumping mechanical seal.

2. physical model

2.1 Calculation model and parameters

Figure 1 shows a typical spiral groove upstream pump mechanical seal end surface model[13], the specific structural parameters shown in Table 1, the spiral groove in the moving ring end surface, the line is the logarithmic spiral, described in the polar coordinates: \( r = r_0 e^{\theta/\phi} \) where \( r_i \) is the inner radius of the moving ring, \( r_g \) is the radius of the top of the slot, \( r_o \) is the outer radius of the moving ring, \( \theta \) is the Spiral expansion angle, \( \phi \) is the helix angle. Figure 2 shows a model of the lubricating film formed between the dynamic and static ring. Since the thickness of the film is micrometers, it is 1000 times magnified in the thickness direction to facilitate observation.

![Fig. 1 The face structure of spiral groove mechanical seal](image)

![Fig. 2 Schematic diagram of micro-gap liquid film](image)

<table>
<thead>
<tr>
<th>Table 1 Geometry parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric parameters</td>
</tr>
<tr>
<td>Inner radius, ( r_i /\text{mm} )</td>
</tr>
<tr>
<td>Groove spiral angle, ( \phi /(^\circ) )</td>
</tr>
<tr>
<td>Outer radius, ( r_o /\text{mm} )</td>
</tr>
<tr>
<td>Groove root radius, ( r_g /\text{mm} )</td>
</tr>
<tr>
<td>Groove width radio, ( \gamma )</td>
</tr>
<tr>
<td>Groove radius radio, ( \beta )</td>
</tr>
<tr>
<td>Groove depth, ( h_c /\mu\text{m} )</td>
</tr>
<tr>
<td>Number of grooves, ( N_s )</td>
</tr>
<tr>
<td>Film thickness, ( h _f /\mu\text{m} )</td>
</tr>
</tbody>
</table>

2.2 Meshing and boundary conditions

\( 1/N_g \) of the liquid film is selected as the calculation domain to research due to the spiral groove are arranged periodically. The grid is meshed with the unstructured grid with the pretreatment software Gambit. In order to make the simulation results more reliable, the uniaxiality of the single-period liquid film is measured. The measured parameters are the opening force, and the operating conditions are at the running speed is 3000rpm and the medium pressure is 0.2MPa. According to the results in Table 2, Considering the convergence speed and accuracy, we use the scheme 2 for meshing, and the result is shown in Fig. 3.
Fig. 3 1/N fluid film mesh and boundary conditions

Table 2 Calculating results of opening force of different meshing schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Length and width meshing size (mm)</th>
<th>Number of layers in thickness direction</th>
<th>Mesh number</th>
<th>Opening force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>12</td>
<td>167099</td>
<td>25.04</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>12</td>
<td>467572</td>
<td>25.26</td>
</tr>
<tr>
<td>3</td>
<td>0.05</td>
<td>16</td>
<td>886077</td>
<td>25.59</td>
</tr>
<tr>
<td>4</td>
<td>0.03</td>
<td>16</td>
<td>2463640</td>
<td>25.68</td>
</tr>
<tr>
<td>5</td>
<td>0.02</td>
<td>20</td>
<td>5543099</td>
<td>25.86</td>
</tr>
</tbody>
</table>

The boundary conditions are installed in the Gambit, as what is shown in the Fig 3. The spiral groove within the liquid film of water is set to rotate and the micro-gap liquid film water body is set to rest. The spiral groove of the three axial side and groove bottom are set as moving surface, and the stationary ring surface is set as a stationary wall surface. The inlet pressure is equal to the high pressure side seal medium pressure, the outlet pressure is the atmospheric pressure. The solid particle density is 3450 kg/m³, and the viscosity of the continuous medium equivalent viscosity is μ = 0.04 Pa·s. The particle inlet is the inner diameter of the spiral groove.

3. Numerical Method

3.1 Governing equation

In this paper, Eulerian multiphase flow model is chosen as the computational model of micro-gap flow. This model considers each phase as a different fluid and solves the momentum equation and continuous equation of each phase. The phases share a single pressure field. Each point of space has its own different velocity, temperature and density of different fluids. These fluids coexist in the same space and penetrate each other, and have different volume fractions, and there is a slip between the phases. The specific equation is as follows:

Mass conservation equation

$$\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) = \sum_{p} (m_{pq} - m_{qp}) \tag{1}$$

where $\alpha_q$, $\rho_q$, $\vec{v}_q$ are volume fraction, density and velocity of $q$ phase respectively and $m_{pq}$ characterizes the mass transfer from phase $p$ to phase $q$, and $m_{qp}$ characterizes the mass transfer from phase $q$ to phase $p$.

Momentum equation

$$\frac{\partial}{\partial t}(\alpha_q \rho_q \vec{v}_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q \vec{v}_q) = -\alpha_q \nabla p + \nabla \cdot \tau_q + \alpha_q \mu_q \nabla \cdot \vec{v}_q + \sum_{p} (R_{pq} + m_{pq} \vec{v}_p - m_{qp} \vec{v}_q) \tag{2}$$

where $p$ is the pressure shared by all phases, $R_{pq}$ is an interaction force between phases, $\vec{v}_{pq}$ is the interphase velocity, and $\tau_q$ is the pressure-strain tensor of the $q$-th phase is calculated as:

$$\tau_q = \alpha_q \mu_q (\nabla \vec{v}_q + \nabla \vec{v}_q^T) + \alpha_q (\lambda_q - \frac{2}{3} \mu_q) \nabla \cdot \vec{v}_q \vec{I} \tag{3}$$

where $\mu_q$ and $\lambda_q$ are the shear and bulk viscosity of phase $q$, and $\vec{I}$ is unit tensor.
Gas transport equation

\[
\frac{\partial}{\partial t}(\alpha \rho v_i) + \nabla \cdot (\alpha \rho v_i v_j) = R_v - R_c
\]  

(4)

where \( v \) is the vapor phase, \( \alpha \) is the volume fraction of the gas phase, and \( R_v, R_c \) are the bubble generation and destruction of the source item. The calculation formula is as follows:

If \( p \leq p_v \),

\[
R_v = F_{\text{sup}} \frac{3 \alpha_{\text{sat}} (1 - \alpha_{\text{sat}}) \rho_v}{g \gamma_B} \frac{2}{3} \frac{p_v - p}{\rho_v}
\]

(5)

If \( p \geq p_v \),

\[
R_c = F_{\text{cond}} \frac{3 \alpha_{\text{sat}} \rho_v}{g \gamma_B} \frac{2}{3} \frac{p - p_v}{\rho_v}
\]

(6)

where \( \gamma_B \) is the bubble diameter, \( \alpha_{\text{sat}} \) is the volume fraction of gas core, \( P_s \) is the saturation pressure, \( F_{\text{sup}} \) is the evaporation coefficient, and \( F_{\text{cond}} \) is the condensation coefficient.

3.2 Cavitation model selection

There are two cavitation models in the Fluent Eulerian multiphase model: the Zwart-Gerber-Belamri cavitation model and the Singhal et al cavitation model. The Zwart-Gerber-Belamri cavitation model is more reasonable than the Singhal et al cavitation model, and the stability is also good. Therefore, Zwart-Gerber-Belamri cavitation model is adopted in this paper [10].

3.3 Simplified conditions

In order to facilitate the calculation, according to the characteristics of the object to make the following assumptions:

(1) the fluid flow of film is laminar [13-14], and the continuity hypothesis is applied;

(2) ignore the body forces, such as gravity and centrifugal force;

(3) the solid particle is spherical and uniform in size, and regardless of phase transition;

(4) does not consider the impact of friction heat on the medium, that is considered isothermal state, temperature is 25 °C;

(5) here is no slip velocity between seal surface and fluid medium;

(6) ignoring the effect of micro-deformation of seal ring on flow field.

3.4 Numerical calculation method and comparison model

Using the double-precision model and the pressure-velocity coupling method uses the Phase Coupled SIMPLE algorithm, the momentum adopts the first order upwind difference scheme, and the volume fraction adopts the first order upwind difference scheme.

In order to study the effect of solid particles on the lubrication performance of upstream pumping mechanical seal considering the cavitation effect, the following two models are selected for comparative analysis. Model 1: only consider the cavitation effect, that is gas-liquid two-phase model; Model 2: adding solid particles and cavitation effect, that is gas-liquid-solid three-phase model.

3.5 Adaptive verification of cavitation model

In order to verify the applicability of the cavitation model in the gas-liquid model and the gas-liquid-solid model, the cavitation area is compared with the cavitation area in the literature [4]. Figure 4 (b) and (c) show the distribution of the cavitation area in accordance with the experimental results in Fig. 4 (a).

![Fig.4 Validation of cavitation model applicability](image)

(a) experimental results (b) Gas-liquid simulation results (c) Gas-liquid-solid simulation results

4. Calculation results and analysis

4.1 Effect of solid particles on cavitation

Figure 5 shows the distribution of the bubble volume fraction along the different thicknesses of the two models when the medium pressure is 0.2MPa, the rotating speed is 3000rpm and the particle inlet volume fraction is 0.2.

It can be seen from the model 1 in Fig. 5 that there is a large cavitation area at the inner diameter of the spiral groove and at the root when there is no solid particles, which indicated that the cavitation is the result of the pumping effect and the gradual step effect. The spatial distribution of the cavitation area of model 2 is similar to that of model 1, but is smaller than that of model 1, because the existence of micrometer-sized particles increases the apparent viscosity of continuous medium phase [16], and increased fluid movement resistance, which inhibited the gas-liquid mass transfer process to a certain extent. This indicates that the existence of particles inhibited the degree of cavitation to a certain extent, and making the cavitation area and the volume fraction of vacuoles decreased.

From the Fig. 5, we can also see that the cavitation area is mainly distributed in the liquid film under z = 0μm section, and the
variation rule of the cavitation area along the thickness direction is the same in the two models. So, the \( z = 0 \mu m \) cut plane is selected to study the influence of different particle diameters, inlet volume fraction and different working conditions on the cavitation and lubrication performance of the mechanical seal liquid film.

4.2 Effect of particle diameter on cavitation

Figure 6 shows the comparison of the volume fraction distribution of the bubble phase in the model 1 and model 2 (\( d = 0.5\mu m \), \( d = 1.0\mu m \), \( d = 1.5\mu m \), \( d = 2.0\mu m \)) when the medium pressure is 0.2MPa, the rotating speed is 3000rpm and the particle inlet volume fraction is 0.2.

It can be seen from Fig. 6 that both the cavitation area and the bubble volume fraction in the model 2 are smaller than those in the model 1, and the cavitation area and the maximum bubble volume fraction also increase with the increase of the particle diameter. When the inlet volume fraction is constant, the increase of the particle diameter reduces the degree of cavitation inhibition to a certain extent and the cavitation area becomes larger. At the same time, it can be found that the boundary of the cavitation region are smooth when the particle diameter is 0.5\( \mu \)m and 1.0\( \mu \)m, which indicates that the cavitation area is stable, and as the particle diameter is larger than 1\( \mu \)m, the boundary becomes no longer smooth, and the stability of the film is deteriorated.

4.3 Effect of particle inlet volume fraction on cavitation

Figure 7 shows the comparison of the volume fraction distribution of the bubble phase in the model 1 and model 2 (\( V_f = 10\% \), \( V_f = 15\% \), \( V_f = 20\% \), \( V_f = 25\% \)) when the medium pressure is 0.2MPa, the rotational speed is 3000rpm and the particle diameter is 1.0\( \mu \)m.

It can be seen from Fig. 7 that cavitation area and bubble volume fraction in model 2 are significantly smaller than those in model 1, because the presence of particles inhibits the degree of cavitation, and it can be seen that when the inlet volume fraction increased, the cavitation area of liquid film decreased and the volume fraction of bubble phase did not change obviously, which indicated that when the volume fraction of the particles pumped out from the inner diameter increased, and the effect is opposite to the effect of increasing the particle diameter. And the smoothness of the boundary of the cavitation area increases with the increase of the particle volume fraction, which improved the stability of liquid film.

![Fig.5 Distribution of bubble volume fraction in different sections along the film thickness](image)

![Fig.6 Distribution of bubble volume fractions in different particle diameters](image)

![Fig.7 Distribution of bubble volume fractions in different particle inlet volume fraction](image)
4.4 Effect of particles on cavitation under different working conditions

Figure 8 shows the comparison of the volume fraction of the bubble phase with the cavitation area at different rotating speeds and media pressures for the two models with particle diameter of 1μm and inlet volume fraction of 0.2.

It can be seen from Fig. 8 that there is no cavitation between the two models when the rotating speed is 1000rpm, so there is no difference between the cavitation area and the bubble volume fraction. Under certain pressure, the cavitation area and the volume fraction of the cavities increase obviously with the increase of the rotating speed, which is caused by the increase of the cavitation degree of the film. Due to the presence of solid particles, the cavitation area and bubble volume fraction of model 2 are significantly reduced compared to model 1. At the same speed, with the increase of the medium pressure, the cavitation area decreased slightly and the bubble volume fraction did not change obviously, which indicated that the medium pressure had little effect on the cavitation degree.

![Image of Fig. 8: Distribution of bubble volume fractions in two models under different operating conditions](image)

4.5 Effect of particle diameter on sealing performance

Figure 9(a) shows the variation of opening force with particle diameter at different rotating speeds when the medium pressure is 0.2MPa and the particle inlet volume fraction is 0.2. It can be seen from Fig. 9(a) that the opening force of the two models increases with the increase of rotating speed. When the rotating speed is 1000rpm, the opening force of liquid film increases with the increase of particle diameter, and the liquid film does not cavitate, which is mainly due to the increase of the maximum static pressure effect caused by enhanced. When the rotating speed is 2000-5000rpm, the opening force of liquid film does not increase with the increase of particle diameter, but increases first and then decreases, and the maximum opening force corresponds to the increase of particle size. Which is the result of the combined effect that the increase of particle diameter leads to the decrease of cavitation inhibition degree and the increase of the cavitation degree due to the increase of the rotating speed. When the rotating speed is 5000rpm, the opening force of liquid film with particle diameter of 2.0μm is smaller than that of the pure liquid film under the same operating conditions, which indicates that the cavitation is too intense due to the rotational speed and particle diameter are the maximum values of the study range, which leads to the decrease of the opening force.

Figure 9(c) shows the variation of opening force with particle diameter at different medium pressure when the rotating speed is 3000rpm and the particle inlet volume fraction is 0.2. It can be seen from Fig. 9(c) that the opening force of the two computational models increases as the medium pressure increases. This is due to the medium pressure increases, the liquid film cavitation decreased, which make the degree of cavitation is not too severe to ensure the stability of the liquid film. Under different medium pressure, the opening force increases with the increase of particle diameter, and then increases first and then decreases, which is consistent with the above rules.

Figure 9(b) shows the change of friction torque with particle size at different rotating speeds. It can be seen from Fig. 9(b), with the increase of rotating speed, the friction torque increases, but the effect of friction torque on particle diameter is not obvious. Only when the particle diameter is about 0.5μm, the friction torque has obvious effect on the friction torque, and a decrease occurred, which shows that when the particle diameter is about 0.5μm, can have a favorable impact on opening force and friction torque of the seal in the working condition range.

Figure 9(d) shows the variation of friction torque with particle diameter at different medium pressure when the rotating speed is 3000rpm and the particle inlet volume fraction is 0.2. As can be seen from Fig. 9(d), the frictional torque of the two
computational models increases as the medium pressure increases. Under different media pressure, the change of friction torque is same as the different speed mentioned above in Fig. 9(b).

![Graphs showing variation of force and friction torque with medium pressure and particle volume fraction.](image)

**Fig. 9** The variation rule of sealing performance parameters at different rotating speed and medium pressure with particle

### 4.6 Effect of volume fraction of particles on sealing performance

Figure 10(a) shows the variation of opening force with particle inlet volume fraction at different speeds when the medium pressure is 0.2MPa and the particle diameter is 1.0μm. Figure 10(c) shows the variation of opening force with particle inlet volume fraction at different medium pressure when the rotating speed is 3000rpm and the particle inlet volume fraction is 0.2. It can be seen that the opening force of the film increases with the increase of the rotating speed, and increases with the increase of the volume fraction of the particles, which is due to the increase in particle volume fraction of the entrance enhanced the degree of inhibition of cavitation, so that the cavitation will not be too intense to ensure the stability of the liquid film and the maximum static pressure to enhance the opening force. It can be seen from Fig. 10(c) that the opening force of the liquid film increases with increasing medium pressure and increases slightly as the volume fraction of the particles increases. When the rotating speed is 3000rpm and Medium pressure is 0.2Mpa, the volume fraction of the inlet of the particle has a great influence on the opening force of the liquid film, which indicates that the cavitation of the liquid film is relatively unstable, and the solid particles obviously enhance the cavitation stability and liquid film pressure stability.

Figure 10(b) shows the variation of friction torque at different speeds for the two models. It can be seen from Figure 10(b) that the friction torque increases as the rotating speed increases, and as the volume fraction of the particles increases, the friction torque decreases slightly, which indicates that the particle volume fraction has little effect on the friction torque. The presence of particles helps to improve the dynamic pressure lubrication to a certain extent from the point of view of the liquid film, and reduce the friction resistance. Figure 10(d) shows the variation of friction torque at different medium pressure for the two models. It can be seen from Fig. 10(d) that the friction torque does not change significantly with the increase of the medium pressure, which indicates that the medium pressure has little effect on the friction torque under the different volume fraction of the particles, and the variation of friction torque with the volume fraction of particles under the same medium pressure is consistent with that under different rotating speeds.
5. Conclusion

Based on the Eulerian multiphase flow model, the effect of solid particle on cavitation and lubrication characteristics of upstream pumping mechanical seal liquid membrane has been successfully studied. Some conclusions are made.

(1) The existence of the particles can restrain the cavitation to a certain extent, which can reduce the cavitation area and the bubble volume fraction.

(2) The cavitation area and the volume fraction of the bubble increased with the increase of the particle diameter, which indicated that the inhibition of cavitation was weakened by the increase of particle diameter. The cavitation area decreased with the increase of the volume fraction of particles, which indicated that the increase of the volume fraction of the particles increased the cavitation inhibition. The presence of particles improved the opening force of liquid film to a certain extent and increased with the increase of particle volume fraction, but the effect of particle diameter on opening force was different under different rotating speed and different medium pressure. The influence of friction torque is not obvious with the change of particle diameter, and when the particle diameter is about 0.5μm, can have a favorable impact on opening force and the friction torque of the seal in the working condition range. The friction torque is only slightly decreased with the increase of the volume fraction of the particle inlet, and the presence of particles helps to improve the dynamic pressure lubrication to a certain extent from the point of view of the liquid film.

(3) No cavitation occurred when the rotating speed is 1000rpm, and under the same pressure, the cavitation area and the void volume fraction of the two models increase obviously with the increase of the rotating speed, which is the rule that the cavitation degree of liquid film increase with the increase of the rotating speed, is not changed. Due to the presence of solid particles, the cavitation area and bubble volume fraction of model 2 are significantly reduced compared to model 1. At the same speed, with the increase of the medium pressure, the cavitation area decreased slightly and the bubble volume fraction did not change obviously, which indicated that the medium pressure had little effect on the cavitation degree.
Acknowledgments

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Nomenclature

- $F$: Opening force [N]
- $M_f$: Friction torque [N.m]
- $V_f$: Particle volume fraction (%)
- $n$: Rotating speed [rpm]
- $P$: Medium pressure [MPa]
- $d$: Particle diameter [μm]

References