Analysis on pressure characteristics of pump turbine guide bearing rotating sump based on VOF model

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Abstract: With the technology of Computational Fluid Dynamics (CFD), this paper conducts a 3D numerical simulation for the oil and gas flow field in the Pump turbine guide bearing rotating sump. VOF model is adopted in this simulation. This study calculates distribution of the oil-air phase and characteristics of the pressure. The influence of sump rotating speed, oil level and oil viscosity on the pressure at the inlet of oil-immersion plate are discussed. The results demonstrate that the static pressure at the inlet is roughly proportional to oil level. Too low level may result in the separation between lubrication oil and supply hole on the oil-immersion plate, which then disables the oil supply. The static pressure at the inlet increases parabola as the sump rotating speed increases. To ensure the supply pressure, the unit is not suitable for long time operation under low rotating speed. The temperature-viscosity effect of the lubricant oil has little influence on the oil pressure at the supply hole. This paper provides a theoretical base for the safe design and operation of the pump turbine rotating sump, and offers the inlet boundary condition for the analysis of the oil film dynamic characteristics of the turbine guide bearing.

1. Introduction
The pump turbine guide bearing is installed on the shaft journal near to the turbine. It is used to limit the displacement of the journal, prevent the winging of the shaft and keep the axis stable[1]. At present, the common turbine guide bearings include rubber bearing with water lubrication, sleeve bearing with light oil lubrication and segment bearing with light oil lubrication. This paper focus on the rotating
sump of the sleeve guide bearing of pump turbine and researches the oil gas distribution and pressure characteristics in it.

The pressure feature of the rotating sump, especially oil pressure of the supply inlet on the oil-immersion plate, is very important for the generation of the oil film in the clearance of the guide bearing. Some researches on it have been done. He Kaixi\(^2\) improves the method to calculate the sleeve guide bearing with slight oil lubrication, which is more accurate than traditional method. Chen Zhu\(^3\) adopts VOF model to do 2D numerical simulation for the pressure distribution in a hydroturbine guide bearing and gets the pressure of oil supply hole based on CFD method.

The oil and gas two-phase flow calculation for the rotating sump is a typical problem of free surface liquid motion. At present, volume tracking method is an efficient method to deal with the free surface liquid motion. It includes MAC (Marker and Cell) and VOF (Volume of Fluid) method. MAC method has advantages of clear physics concept and simple computation process, but is not suitable for the 3D complex flow. VOF\(^4,5\) can compensate for the shortcomings of MAC. In VOF method, volume function \(F\) (The rate of occupied volume of fluid in an element to the whole volume of the element) is defined. The location of free liquid surface is calculated through building and solving the transportation and diffusion equation of \(F\). As \(F\) is equal to 1, it means the element is filled with liquid; As \(F\) is equal to 0, it means the element has no liquid. As \(F\) is between 0 and 1, it means the element is filled with both liquid and gas, in which the element is called free surface element.

Based on 3D CFD method, this paper researches the oil gas distribution and pressure characteristics of the pump turbine rotating sump with VOF model and piecewise linear interface reconstruction method. The relation between oil pressure of the supply inlet and sump rotating speed, oil level and oil viscosity is discussed. This paper provides some theoretical basis for the safe design and operation of the pump turbine rotating sump.

2. Mathematical model and numerical method

2.1. Fundamental equation

This paper researches the two phase flow of lubrication oil and air in the rotating sump. The VOF method based on the Finite Volume Method is used to calculate the oil gas distribution and pressure distribution and pressure characteristics. Mixture model is adopted for the two phase flow. N-S equations are solved with numerical method. The 3D incompressible Navier-Stokes equation sets with VOF model and not considering heart conduction are as follows:

Momentum equation:

\[
\frac{\partial}{\partial t} (\rho V) + \nabla \cdot (\rho V V) = -\nabla p + \nabla \cdot [\mu (\nabla V + \nabla V^T)] + \rho g + F
\]

\(\text{(1)}\)

Where \(g\) is acceleration of gravity; \(F\) is body force; \(\mu\) is the dynamic viscosity coefficient of the mixed fluids, which is as follows:

\[
\mu = f \mu_1 + (1-f) \mu_2
\]

\(\text{(2)}\)

Where \(\mu_1, \mu_2\) are the dynamic viscosity coefficients of liquid and gas.
Continuity equation:
\[
\frac{\partial}{\partial t} (\rho) + \nabla \cdot (\rho V) = 0
\]
(3)

Where \( V \) is the common velocity vector of two phase fluid; \( \rho \) is the density of the mixture, which is defined as follows:
\[
\rho = f \rho_1 + (1 - f) \rho_2
\]
(4)

Volume function of the liquid, \( f \), meets the equation below:
\[
\frac{\partial (f \rho)}{\partial t} + \nabla \cdot (f \rho V) = S_f
\]
(5)

Where \( S_f \) is source item of mass transmission of the liquid and gas; piecewise linear interface reconstruction method \(^{[6,7,8]}\) is used in VOF method, in which the free liquid surface of the elements is assumed to be plane, and the plane equation is decided by distribution of the volume components; One step flux is adopted in the calculation of interface flux, which means that only one interface reconstruction calculation is needed in every time step \(^{[9]}\).

2.2. Numerical solution method
Because the simulation uses Mixture model, only one set of momentum equations needs to be solved. The flow variables, such as velocity and pressure, are shared by two phase liquids \(^{[9]}\). Time derivative adopts first order implicit formula. Gradient uses Least Squares Cell Based discrete formula. Discretization of Pressure uses Body Force Weighted formula. Volume Fraction adopts volume reconstruction. Pressure-Velocity Coupling uses PISO scheme which is suitable for transient flow.

3. Computational model and grid

![Diagram of the pump turbine rotating sump.](image)

Figure 1. Diagram of the pump turbine rotating sump.

This paper focuses on the pump turbine rotating sump (Figure 1). The basis structural parameters: external radius of the sump is 902.5mm with internal radius 500mm; external radius of bearing bush is 635mm with internal radius 510mm; the external radius of oil-immersion plate is 870mm; the diameter of oil supply hole is 50mm. The rated rotating speed of the unit is 500r/min. The basis oil level in the sump is about 355mm. The material properties of air and 32# turbine oil are shown as Table 1.
When the unit is in operation, the turbine guide bearing rotating sump rotates with the main shaft, and the oil in it also rotates synchronously. Because of the effect of centrifugal force, the oil level will keep the state of high on the edge and low in the centre. Under the differential pressure, the lubrication oil will enter to the annular oil groove on the internal surface of pads through the supply holes on the stationary oil-immersion plate. With the rotation of shaft, the oil will moved upper along the oil groove and lubricate the whole surface of the journal. Thus it can keep good lubricating between the journal and pads, meanwhile take away quantity of heat.

According to the structure sizes of the rotating sump, and considering the actual details, the paper builds the 3D model to improve computation accuracy. Because the model is complex relatively, the unstructured grid is adopted for convenience. The number of grid is 901448. The model and grid is shown in Figure 2 and Figure 3 respectively.

Because the sump is rotating, the whole zone is defined as rotating zone for convenient computation. The inner wall of the sump rotates with main shaft synchronously and that of guide bearing pads keeps stationary. Pressure inlet and pressure outlet are used for the boundary conditions.

To discuss the effect of sump rotating speed, oil level and oil viscosity on the oil gas distribution and pressure characteristics, some cases are computed as shown in Table 2.

### Table 1. Material properties.

|                | Air    | 32# Turbine oil |
|----------------|--------|-----------------|
| Density (kg/m³)| 1.225  | 890             |
| Viscosity (kg/m.s) | 1.79e-5 | 0.02848        |

### Table 2. Simulation model parameters

| No. | Rotating speed (rpm) | Oil level (mm) | Oil viscosity (kg/m.s) |
|-----|-----------------------|----------------|------------------------|
| 1   | 300                   | 355            | 0.02848                |
| 2   | 400                   | 355            | 0.02848                |
| 3   | 500                   | 355            | 0.02848                |
| 4   | 600                   | 355            | 0.02848                |
| 5   | 700                   | 355            | 0.02848                |
| 6   | 500                   | 250            | 0.02848                |
| 7   | 500                   | 300            | 0.02848                |
| 8   | 500                   | 400            | 0.02848                |
| 9   | 500                   | 450            | 0.02848                |
| 10  | 500                   | 355            | 0.02000                |
| 11  | 500                   | 355            | 0.02500                |
| 12  | 500                   | 355            | 0.03500                |
4. Results and analysis

4.1. Effect of oil level to the oil gas distribution and pressure characteristics

Keeping the rated rotating speed of 500rpm, this paper does computation in the cases with oil level of 250mm, 300mm, 355mm, 400mm and 450mm respectively. Figure 4 shows the oil and gas distribution in stable operation. The oil-immersion plate divides the interface of oil and gas into upper and lower parts. Due to the gravity, the radius of upper interface is short while the lower is long. As the oil level decreases, the radius of the interface increases. According to the trend, the radius of the interface will longer than that of oil-immersion plate when the level decreases to 100mm. In that case, the oil will be separated from the oil supply holes, and cannot be provide for the oil film in the clearance of the guide bearing. Therefore, the oil level should not less than 100mm to ensure the continuity of the oil supply.

Figure 5. Static pressure contour on axial section of the sump with rotating speed of 500rpm and oil level of 355mm (case No.3).

Figure 6. Static pressure distribution on the external surface with rotating speed of 500rpm and oil level of 355mm (case No.3).
Figure 5 shows the oil pressure distribution on the axial section of the sump with the rated rotating speed of 500rpm and oil level of 355 mm (case No.3). As the effect of centrifugal force, oil pressure increases as the radius increases. The maximum pressure is up to 0.234 MPa. Figure 6 shows the pressure distribution on the external surface of the bearing bush. The oil supply holes are located on whose radius is maximum on the immersion plate. In addition, the pressure is maximum on the surface. From the figure, the oil pressure at the supply holes is about 0.184 MPa.

![Pressure Distribution Diagram]

**Figure 6.** Effect of oil levels on the oil supply pressure

The effect of oil level in the sump on the pressure at the oil supply holes is shown in Figure 7. With the rise of oil level, the dynamic and total pressure at the oil supply holes increases first fast and then slowly. The static pressure increases faster than the dynamic pressure as the oil level rises. Because the oil-immersion plate is circular, the velocity vector at the oil supply holes is tangent of the basis circle. Therefore, it is static pressure but not dynamic pressure that plays the most important role in the oil supply. The static pressure at the holes increases linearly with increase of the oil level. It is easy to get the formulation showing relation between the static pressure at the holes and the oil level under the rotating speed of 500rpm.

\[
P_{\text{static}} = (0.009959h - 1.612) \times 10^5
\]

Where \( P_{\text{static}} \) is static pressure at the oil supply holes, Pa; \( n \) is the rotating speed of the sump, rpm.

4.2. Effect of rotating speed on the pressure characteristics of the sump

Pump turbine usually starts and stops frequently. The unit is often in the state of variable speed. The rotating speed has a great effect on the pressure characteristics in the sump. This paper calculates the pressure feature with the basis oil level of 355mm and rotating speed from low speed 300rpm to runaway speed 700rpm. The influence of rotating speed on the oil pressure at the holes is shown in Figure 8. The dynamic and total pressure increase parabola, and faster than static pressure as the

![Pressure vs. Rotating Speed Graph]
rotating speed increases. As the speed rises from 300rpm to 700rpm, the static pressure increases from $0.71 \times 10^5 \text{Pa}$ to $3.93 \times 10^5 \text{Pa}$ which grew by 453%. Thus the influence of rotating speed on the oil supply pressure is very great. Under the oil level of 355mm, the relation between static pressure at the holes and the rotating speed can be described using the fitting function as follows:

$$P_{\text{static}} = 1.029n^2 - 222.6n + 44770$$

(7)

Where $P_{\text{static}}$ is static pressure at the oil supply holes, Pa; $n$ is the rotating speed of the sump, rpm.

![Figure 8. Effect of rotating speed on the oil supply pressure.](image)

4.3. Effect of oil viscosity on the pressure characteristics of the sump

![Figure 9. Effect of oil viscosity on the oil supply pressure](image)

The viscosity of lubrication oil is usually variable with temperature and pressure. However, the effect of pressure on viscosity should be taken into consideration only under very high pressure$^{[10]}$. When the
oil lubricates in the clearance of the guide bearing, it will consume the mechanical work from the journal. The frictional work transforms to heat and makes the oil temperature rise. Then the oil goes into the sump, results into rise of temperature of the oil in the sump and decreasing of the lubrication oil. This paper calculates the pressure characteristics in the sump with rated rotating speed of 500prm, basis oil level of 355mm and oil viscosity of 0.02, 0.025, 0.02848 and 0.035 kg/m.s. How the oil supply pressure changes over the viscosity can be seen in Figure 9. The static pressure at the holes increases slightly with the viscosity. So rise of the temperature will lead to slight decrease of the static pressure at the supply holes, and has less impact than the rotating speed and oil level.

5. Conclusions
With the VOF model based on Finite Volume Method, this paper studies the oil gas distribution and pressure characteristics in the pump turbine rotating sump. The effect of sump rotating speed, oil level and oil viscosity on the oil supply pressure is discussed. Some conclusions can be drawn:

(1) When the sump is rotating steadily, the oil-immersion plate divides the free surface interface into two parts: the upper one with longer radius and the lower one with shorter radius. The radius of interface will increase with decrease of the oil level. To ensure the oil supply, the oil level should not be less than 100mm.

(2) The static pressure at the supply holes increases linearly as the oil level, and faster than dynamic pressure; the static pressure increases at parabola with increase of rotating speed, but less slowly than dynamic pressure. To ensure safety of the oil supply for the clearance, the guide baring sump is not suitable to operate under the condition of low oil level and low rotating speed.

(3) The temperature-viscosity effect of lubrication oil has little influence on the oil supply pressure. The oil pressure increases slightly as the viscosity increases. The influence can be ignored.

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