Interface stability of magnetic fluid seal for sealing liquid

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Abstract. Theoretically, the velocity distributions of the sealed liquid and magnetic fluid are studied. The velocity of the sealed liquid and magnetic fluid decreases nonlinearly with the increase of the radius. The instability of the interface between magnetic fluid and the sealed liquid is studied. Experimentally, when the rotating speed of the shaft increases, magnetic fluid and the sealed liquid are mixed with each other, and the stability of the interface between magnetic fluid and the sealed liquid is destroyed. The higher the rotational speed of the shaft is, the shorter the time for the interface to remain stable is.

1. Introduction
As a new type of sealing method, magnetic fluid seal has a broad application prospect in sealing liquid with its unique advantages[1-4]. However, in liquid environment, the operation of magnetic fluid seal involves complex physical process, with poor sealing performance, low pressure resistance and short sealing life[5-7]. Previous studies have shown that the performance of magnetic fluid seal in liquid environment is related to the stability of the interface between magnetic fluid and sealed liquid in the seal structure.

In this paper, the stability theory of the interface between two kinds of fluids is studied theoretically and verified by experiments.

2. Theoretical research
2.1 Velocity of magnetic fluid
Fig. 1 shows the structure of magnetic fluid seal for sealing liquid. In the figure, the radius of the rotating shaft is $R_1$, the inner diameter of the pole shoe and the inner diameter of the sealing cavity are $R_2$ and $R_3$ respectively.
The motion equation of magnetic fluid is as follows:

$$\rho_m \frac{dV}{dt} = \rho_m g - \nabla p + \mu_0 M \nabla H + \eta \nabla^2 V$$  \hspace{1cm} (1)$$

When sealing liquid with magnetic fluid, they both have shear motion. It is assumed that magnetic fluid is laminar flow and incompressible, the viscosity of magnetic fluid is constant and the influence of gravity is ignored, the temperature being uniform. Assuming that the pole shoe is concentric with the axis of rotation, the flow of magnetic fluid is axisymmetric. Under the condition of high-speed rotation, the axial and radial components of magnetic fluid velocity can be ignored. Neglecting the influence of the polar teeth on the velocity distribution of magnetic fluid, the magnetic fluid equation in cylindrical coordinate system can be obtained. By solving the above equation and using boundary conditions, the velocity distribution of magnetic fluid can be obtained as follows:

$$v_m = \frac{\omega R_1^2}{R_1^2 - R_2^2} \left( r - \frac{R_2^2}{r} \right)$$  \hspace{1cm} (2)$$

2.2 Velocity of the sealed liquid

The sealed liquid in this paper is ordinary fluid, and the motion equation of ordinary fluid is as follows:

$$\rho \frac{\partial V}{\partial t} + \rho V \cdot \nabla V = \rho g - \nabla p + \eta \nabla^2 V$$  \hspace{1cm} (3)$$

Where $\rho$ is density of ordinary fluid; $V$ is velocity of ordinary fluid; $g$ is gravity constant; $\eta$ the dynamic viscosity coefficient of ordinary fluid.

Because the width of the liquid to be sealed is small in the radial direction, the flow of the liquid to be sealed can be regarded as one-dimensional laminar flow along the tangential direction[8], which ignores the gravity and is incompressible. The flow field is axisymmetric, the axial and radial components of the velocity of the sealed liquid can be ignored under the condition of high-speed rotation of the rotating shaft, and the velocity of each point on the same circle is equal. The velocity distribution of the sealed liquid is as follows:

$$v_l = \frac{\omega R_1^2}{R_1^2 - R_2^2} \left( r - \frac{R_2^2}{r} \right)$$  \hspace{1cm} (4)$$

2.3 Stability of the interface

We can get that the velocity difference between the magnetic fluid and the sealed liquid in the magnetic fluid sealing area is as follows:

$$\Delta v = \omega R_1^2 \left[ \left( \frac{1}{R_1^2 - R_3^2} - \frac{1}{R_1^2 - R_2^2} \right) r + \left( \frac{R_2^2}{R_1^2 - R_2^2} - \frac{R_3^2}{R_1^2 - R_3^2} \right) \frac{1}{r} \right]$$  \hspace{1cm} (5)$$

It can be seen that the speed difference between the magnetic fluid and the sealed liquid is proportional to the rotating speed of the shaft. The higher the rotational speed of the shaft is, the higher the relative flow velocity is, and the easier the contact surface is damaged.

The maximum velocity difference on the interface between magnetic fluid and sealed liquid increases linearly with the increase of shaft speed. When the rotation speed of the shaft is high, the velocity difference between the magnetic fluid and the sealed liquid at the interface is large, which will lead to the occurrence and growth of Kelvin Helmholtz instability on the interface, which has a great impact on the sealing performance of the magnetic fluid.

A higher rotating speed of the shaft may change the motion state of the sealed liquid from laminar flow to turbulent flow, which has a scouring effect on the magnetic fluid at the interface. If the impact force overcomes the attraction of the magnetic field to the magnetic fluid, the magnetic fluid seal will fail; when the rotating speed of the shaft is higher, the discontinuity effect of the interface of two kinds of fluid will also be enhanced, which may cause interface instability. It causes the loss of magnetic fluid. In addition, the interface instability will accelerate the penetration between the two liquids and reduce the seal life of the magnetic fluid seal.
3. Experimental study
In order to verify the above theoretical analysis, the experimental platform of interface stability between magnetic fluid and water is designed in this section. Through experiments, the failure mechanism of magnetic fluid sealing fluid was analyzed.

3.1 Experimental process
The experimental platform of interface stability between magnetic fluid and water is shown in Fig. 2. The experimental platform consists of motor, governor and liquid container.

![Experiment platform of interface stability of magnetic fluid and water](image)

After the container is installed, the lower part and the gap are filled with magnetic fluid, and the upper part is filled with water. The interface between the two fluids is at the upper edge of the gap between the cylindrical surface of the sleeve and the inner surface of the container shell. During the experiment, the motor controlled by the governor drives the shaft to rotate, and the magnetic fluid and water also move with it. The change of the interface can be observed through the transparent container shell.

The magnetic fluid and water are successively injected into the liquid container. Use the governor to call out different shaft speeds and keep the shaft speed unchanged. Observe the change of the interface in the narrow gap, and record the stable operation time under different speeds.

3.2 Results and analysis
When the rotation speed of the shaft is low, there is no obvious change in the interface between the water and the magnetic fluid, and the interface is in a relatively stable state, and the magnetic fluid and water are immiscible; when the rotation speed of the shaft increases gradually, a little magnetic fluid enters into the water, and the interface is in an unstable state; then the water and the magnetic fluid gradually mix together, as shown in Fig. 3. With the increase of the rotating speed, the time for the interface to keep stable becomes shorter and shorter.
Through this experiment, we can analyze the failure mechanism of the magnetic fluid sealing fluid. There is a velocity difference between the magnetic fluid and the sealed fluid at the interface, which leads to the instability of the interface. When the rotation speed of the shaft increases to a certain critical value, with the continuous rotation of the shaft, the two kinds of fluids are mixed with each other. The stability of the interface is destroyed. the magnetic fluid which plays the role of sealing gradually decreases or even disappears, eventually leading to the failure of the seal. The higher the rotational speed of the shaft is, the shorter the time for the interface to remain stable is.

4. Conclusion
The velocity of the sealed liquid and magnetic fluid decrease nonlinearly with the increase of the radius. The experimental results show that when the rotating speed of the shaft increases, magnetic fluid and the sealed liquid are mixed with each other, and the stability of the interface between magnetic fluid and the sealed liquid is destroyed. The higher the rotational speed of the shaft is, the shorter the time for the interface to remain stable is.

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