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Theory of Magnetic Fluid Sealing in Roller Cone Bits

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Abstract: Most of the untapped oil and gas resources in China are buried in deep formations, and drilling technology plays a crucial role in the exploration and development of oil and gas resources in China. Roller bit plays an irreplaceable role in oil and gas drilling, especially for the harsh drilling conditions and formation conditions in deep wells. However, the current situation of low penetration rate, low life, low drilling efficiency, and high cost of cone bits is particularly prominent, and sealing failure is the key factor. Currently, there are mainly two types of sealing for cone bits: radial sealing and metal sealing. Although the existing sealing research results are relatively significant, contact sealing cannot fundamentally solve the wear problem, and thus cannot improve the rotational speed and drilling efficiency. Therefore, this paper presents a magnetic fluid seal structure designed for roller cone bits and provides a theoretical study of it.

Keywords: Roller cone bit; magnetic fluid; sealing structure; theoretical research.

1. Introduction

Magnetic liquid, also known as ferrofluid or ferromagnetic fluid, exhibits both fluid properties and the magnetic characteristics of solid materials. It can provide hydrodynamic and lubricating effects and has been widely applied across various industries, including sealing, damping, and nuclear engineering. Among these applications, magnetic liquid sealing shows broad development prospects. Compared to conventional sealing methods, it offers the following advantages(Morillas et al. 2016, Han et al. 2018, Skalski et al. 2017, Michael 2018, Marinica 2016):

(1) Zero leakage and pollution: With a rationally designed sealing structure and appropriately formulated magnetic liquid—a highly saturated colloidal mixture—the viscosity and other properties of the magnetic liquid can be adjusted via magnetic field strength to achieve optimal sealing performance. This enables reliable sealing even for corrosive, toxic, flammable, or explosive substances.

(2) No wear and minimal energy loss: Contact-based sealing methods suffer from wear, which not only shortens the seal's service life and degrades performance but also consumes more energy. Wear debris can further cause cyclic abrasion, accelerating seal failure. In contrast, magnetic liquid sealing is non-contact, and the base fluid provides lubrication, reducing wear at the sealing interface. It generates less heat and consumes less energy, making it suitable for high-speed rotary sealing.

(3) Bidirectional suitability: Magnetic liquid sealing can be applied in bidirectional sealing without requiring additional structural design. It remains effective under dynamically varying pressure conditions on both sides of the seal.

(4) Long service life and high stability: Depending on the actual operating conditions—such as different temperature ranges and types of sealed media—magnetic liquid seals can be customized with corresponding magnetic liquid formulations and suitably designed structures. A reserve supply of magnetic liquid can also be stored for replenishment, ensuring high stability and a long operational lifespan.

The roller cone bit is widely used in oil and gas resource exploitation, especially in the case of slow drilling speed, low life, low drilling efficiency and high cost. With the development of materials and technology, although the overall life of the cone has been greatly improved, seal failure is still one of the important factors (Hareland et al. 2009).

Magnetic fluid has the characteristics of no leakage, no pollution, no wear, and long life. The non-contact seal can effectively avoid the problem of friction heat generation. The research of magnetic fluid seal includes:

(1) Structure improvement. At high rotational speeds, the centrifugal seal has a pumping effect, and the sealing ability of the magnetic fluid is weakened. At low rotational speeds, magnetic fluid seals play a role and centrifugal sealing performance decreases (Matuszewski 2019); The spiral magnetic fluid combined seal can also solve the leakage problem caused by rotational speed changes (Wang et al. 2022); Design of divergent stepped seal structure (Yang and Li 2016); Research on the performance of segmented magnetic fluid sealing structures (Zhang and Li 2018); Research on mechanical magnetic fluid static combined seals (Wang et al. 2021); Multistage magnetic fluid seals can effectively improve the stability and durability of sealing water (Szczech and Horak 2015).

(2) Improved performance. The interface stability between the magnetic liquid and the sealed liquid medium can be improved by configuring a hydrophobic silicon based magnetic liquid (Szydło 2011); By changing the viscosity of the magnetic fluid, the critical pressure value and service life of the sealing structure are increased (Li et al. 2018). There has been relatively mature research on magnetic fluid static seals, but the dynamic sealing conditions are complex, and it is necessary to consider the performance of magnetic fluid to extend life and increase stability. Adding flexible pole shoes to the pole teeth can significantly improve the sealing ability (Zhang et al. 2016); Improving the emulsification phenomenon at the sealing interface can improve the sealing stability (Bhimani and Wilson 2013); The stability of the base carrier liquid can be improved by adding special active agents (Kim 2010); Hendraningrat and Torsaeter (2014) introduce the research status of nanofluids in detail, summarize the methods to improve the stability of nanofluids, and improve the stability of silica nanofluids when contacting with external media by adding stabilizers.

(3) In the application of stern shaft sealing for ships,

researchers conducted pressure resistance and sealing life tests on magnetic liquids with different base fluids. They found that under certain conditions, silicone oil-based magnetic liquids exhibit better sealing performance and longer service life compared to siloxane-based ones, with rotational speed inversely proportional to sealing duration (Szczech et al. 2015).

Researchers applied magnetic liquid sealing to a rotary blood pump, employing engine oil-based magnetic liquid to seal water and blood. By adding a baffle in front of the pole teeth, they achieved leak-free operation for over a hundred days (Matuszewski 2016).

2. Theoretical Study on Magnetic Fluid Seal

The magnetic fluid sealing structure of the roller bit is located in the sealing chamber composed of the roller and the tooth palm, and is composed of magnetic fluid, pole shoe and permanent magnet. A number of pole teeth are machined on the inner surface of the pole shoe. Using the fast response of the magnetic fluid to the external magnetic field, the magnetic fluid is positioned and directionally moved to the sealing clearance formed between the pole teeth and the shaft with magnetic conductivity. Multiple closed magnetic conductive circuits are formed by the pole shoe, permanent magnet and the shaft. A strong magnetic field is formed in the sealing clearance between the pole teeth and the shaft, generating multiple stable "O" shaped liquid sealing rings, and it forms a multistage magnetic fluid seal.

The magnetic fluid seal primarily consists of two components: the magnetic fluid itself and the sealing structure assembly. The sealing structure assembly comprises components such as permanent magnets, magnetic poles, pole teeth, and a permeable shaft. Multiple pole teeth are machined onto the outer cylindrical surface of the rotating shaft or the inner cylindrical surface of the pole pieces. Leveraging the characteristic of magnetic fluids to respond rapidly to an applied magnetic field, the magnetic fluid is positioned and directionally moved into the sealing gap formed between the magnetically permeable pole teeth and the rotating shaft. Multiple closed magnetic circuits are formed by the magnetic poles, permanent magnets, and the rotating shaft. Constituting a multi-stage magnetic fluid seal, as shown in Figure 1(a).

When a pressure difference exists across the seal, a pinhole-like micro-rupture can appear in the middle of the sealing gap. The magnetic fluid seal ring may displace or even rupture, allowing the sealed medium to flow from the high-pressure side to the low-pressure side through this pinhole. This leads to a sudden pressure increase in the next seal chamber and a decrease in the previous chamber's pressure, as shown in Figures 1(b), (c), and (d). Simultaneously, due to magnetic forces, the seal ring also possesses self-healing capabilities. When the pressure decreases back within its bearing capacity range, the ruptured magnetic fluid will automatically recover under the influence of the magnetic field force.

If the pressure continues to increase, similar to a labyrinth seal, the pressure is transmitted across each individual seal ring, decreasing step by step until an effective seal is re-established. This mechanism ensures that the overall pressure-bearing capacity of the magnetic fluid seal equals the sum of the pressure capacities of the magnetic fluid at all pole teeth.

Based on the sealing principle of magnetic fluids, it can be concluded that the seal fails when the pressure of the medium being sealed exceeds the maximum pressure-bearing capacity of the magnetic fluid seal.

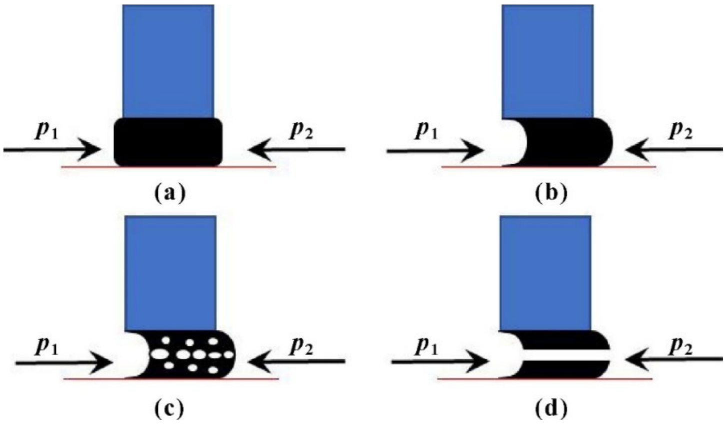

Figure 1. Single-stage magnetic fluid seal

Assuming the magnetic fluid has a velocity potential, then:

$$V = -\nabla\varphi_V \tag{1}$$

For an incompressible magnetic fluid, we have:

$$(\nabla M)_H = \frac{\partial M}{\partial T}\nabla T \tag{2}$$

$$M\nabla H = \nabla\int_0^H M dH - \int_0^H \frac{\partial M}{\partial T}\nabla T dH \tag{3}$$

Let the distance between the magnetic fluid and the reference point be $\boldsymbol{h_m}$, then:

$$\rho g = -\nabla\rho g h_m \tag{4}$$

The known vector identities are:

$$V \cdot \nabla V = \nabla\left(\frac{1}{2}V^2\right) - V \times (\nabla \times V) = \nabla\left(\frac{1}{2}V^2\right) \tag{5}$$

$$\nabla^2 V = \nabla(\nabla \cdot V) - V \times (\nabla \times V) = 0 \tag{6}$$

The general expression of Bernoulli equation of magnetic fluid is:

$$\nabla(-\rho_m \frac{\partial \varphi_V}{\partial t} + \frac{1}{2}\rho_m V^2 + \rho_m g h + P^* - \mu_0 \sum_0^H M dH) + \mu_0 \sum_0^H \frac{\partial M}{\partial T} \nabla T dH = 0 \qquad (7)$$

$$P^* = P + P_m + P_s \qquad (8)$$

In the above formulas, ρ_m is the density of magnetic fluid (kg/m^3); φ_V is the velocity potential (m^2/s); V is the speed of magnetic fluid (m/s); P is the pressure exerted on the magnetic fluid (Pa); P_m is the magnetizing pressure of magnetic liquid, $P_m = \mu_0 \int_0^H MdH(Pa)$; P_s is the hysteresis compression pressure of magnetic fluid, $P_s = \mu_0 \int_0^H \rho_m \frac{\partial M}{\partial \rho_m} dH(Pa)$; M is the magnetization (T); H is the magnetic field strength (A / m); μ_0 is the vacuum permeability (H / m).

After simplification:

$$P^* - \mu_0 \int_0^H MdH = c \qquad (9)$$

When the magnetic field line distribution is approximately the same as the magnetic field line distribution, $P_1^* = P_1$, $P_2^* = P_2$. The pressure resistance formula of magnetic liquid sealing water is:

$$\Delta P = P_1 - P_2 = \mu_0 \int_{H_2}^{H_1} MdH \qquad (10)$$

P_1、P_2 respectively represent the pressure of the low pressure side and the high pressure side, H_1、H_2 respectively represent the magnetic field strength of the low pressure side and the high pressure side, set H_{max} and H_{min} are the maximum and minimum magnetization strength in the magnetic liquid, when H_1 reaches H_{max}, H_2 reaches H_{min}, the difference of magnetic field force obtains the maximum value, so the maximum sealing pressure formula of the magnetic liquid can be expressed as:

$$\Delta P_{max} = P_1 - P_2 = \mu_0 \int_{H_{min}}^{H_{max}} MdH \qquad (11)$$

When the whole magnetic fluid sealing film is in the saturated magnetization state, the above formula can be recorded as:

$$\Delta P_{max} = P_1 - P_2 = \mu_0 \int_{H_{min}}^{H_{max}} M_s dH = \int_{B_{min}}^{B_{max}} M_s dB = \mu_0 M_s (B_{max} - B_{min}) \qquad (12)$$

M_s is the saturation magnetization of magnetic liquid (A / m). For magnetic liquid, it is approximately equal to air and can be recorded as 1. Generally, magnetic liquid adopts multi-stage sealing, and its total pressure resistance is the sum of each unipolar pressure:

$$\Delta P = \sum_{i=0}^{N} \mu_0 M_s (H_{max} - H_{min}) = \sum_{i=0}^{N} M_s (B_{max} - B_{min}) \qquad (13)$$

When the magnetic field strength of the polar tooth in the sealing clearance is known, the theoretical pressure resistance value of the magnetic fluid seal can be obtained.

3. Conclusion

This paper introduces a novel magnetic fluid seal structure for roller cone bits, designed to address the critical limitations of conventional contact seals in deep-well drilling. The theoretical investigation suggests that this non-contact sealing mechanism can effectively mitigate the wear and friction issues inherent in existing radial and metal seals. This approach presents a promising pathway to substantially enhance the service life and rotational speed of roller bits, ultimately improving drilling efficiency and reducing operational costs in harsh downhole environments. Future work should focus on the experimental validation and optimization of this design for practical application.

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