Flow Characteristics Considering the Temperature Viscosity of Oils in the Gap based on Micro Geometric Roughness Fractal Surface

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Abstract. Due to the limitation of manufacturing conditions in China, the valve core will always exhibit random, disordered and multi-scale micro geometric characteristics in recent years. Based on the fractal features of the micro-scale surfaces of the cores and the chambers of a multi-way valve, this research establishes 3-danisotropic models for the surface shapes of the valve cores and chambers using the Weierstrass-Mandelbrot (W-M) function. Then, the boundary conditions of the Navier slip model and computational fluid dynamics (CFD) are used to analyse the flow characteristics of the hydraulic oil in the gap and the wall slip. The research results demonstrate that the surface roughness of the solid walls exerts a significant influence on the flow characteristics of the hydraulic oil as it flows in the gaps: the greater the surface roughness, the higher the probability of occurrence of slip between the surfaces of the solid walls. With varying surface roughness of the solid walls, the greater the slip coefficient \( b \) is, the larger the slip velocity on the walls, and the greater the flow velocity of the hydraulic oil in the whole gap; meanwhile, this phenomenon occurs when the temperature difference between the upper and lower walls increases as well, and the flow velocity of the hydraulic oil increases significantly.

1. Introduction

From a macro-scale perspective, wall slip exerts an insignificant influence on internal leakage [1]. However, the gaps between the valve cores and chambers are present at the micro- to nano-scales. As a result, wall slip inevitably results in changes in the amount of leakage and the associated flow characteristics [2, 3]. However, existing studies mainly focus on the influences of wall slip on the friction force and the bearing capacity of the oil films. As demonstrated in many experimental studies, wall slip [3, 4] and hydrodynamic pressure [5] are found in most liquid-solid interfaces. Meanwhile, boundary slip can reduce the thickness of the momentum boundary layer, increase the thickness of the thermal boundary layer [6], and increase the critical unstable Reynolds (Re) number. In addition, it reduces the maximum transient growth rate of the initial disturbance in the fluids and the non-normality of the linear Navier–Stokes equation [7]. Some American scientists consider the study of boundary slip in fluid flows and the dynamics thereof, to be a key future direction for research in fluid mechanics [8].

In recent years, theoretical and experimental research has demonstrated that boundary slip is directly related to the surface roughness. For example, a larger slip can be generated on a surface with...
poor wetting ability caused by its large surface roughness [9], and with the increase of the surface roughness of the solids undergoing relative motion, the slip length and velocity increase accordingly [10]. Cottin-Bizonne et al. [11] studied the influence of the morphology of irregular surfaces on the slip process through the use of a molecular dynamics simulation and continuous fluid dynamics. The research results indicated that a small variation in surface roughness is expected to lead to a significant difference in the slip effect. The experiment carried out by Granick et al. [12] also demonstrated that the boundary slip is related to the roughness: the rougher the surface, the smaller the probability of occurrence of slip. Yunlu Pan et al. [13] found that effective boundary slip induced by surface roughness of fully wetted rough surface keeps negative and further decreases with increasing Ra or decreasing Rsm. ZHANG Jing-yang et al. [14] studied the effects of sliding boundary of aerodynamic compliant foil bearing, found that influence of any sliding conditions on capacity was amplified and on deflection angle was cut down, when rotation speed, eccentricity or gas dynamic viscosity increase. Therefore, it is thought that roughness exerts a significant influence on the boundary slip of liquid-solid interfaces and the flow characteristics of the fluids at a micro-scale.

The rest of this paper organized as follows. Section 2 describes the fractal theory which is introduced to characterise the geometric features such as randomness, multi-scalability, and self-affinity of micro-surfaces such as are found on valve cores and chambers. Meanwhile, 3-d anisotropic models are constructed of the surface shapes of valve cores and chambers using the Weierstrass-Mandelbrot (W-M) function. Section 3 studies the flow characteristics of a hydraulic oil in the gaps and the boundary slip using the boundary conditions of the Navier slip model and computational fluid dynamics. Conclusions are provided in Section 4.

2. The establishment of the model of the gap between the valve cores and chambers

2.1. Construction of the flow model of the fluids in the gaps

The slide-valve hydraulic valve is an important control element used in hydraulic excavators. By connecting and disconnecting the oil circuits using the motion of the valve cores relative to the valve chambers, it changes the flow direction of the hydraulic oil, so as to control the direction of motion of the executive device. Figure 1 shows the layout of a slide-valve directional valve: P and T represent the oil inlet and the return-oil inlet respectively, while A and B indicate the inlets connected to the executive device.

![Figure 1. Schematic of spool and valve chamber.](image_url)
The 3-d model of the fluid flow in the gap between the mating surfaces of the valve core and chamber is established to investigate the fluid flow therein. The 3-d anisotropic models are shown in Figure 2. As shown in Figure 3, the upper and lower surfaces represent the surfaces of the valve cores and chambers respectively: both are small squares measuring 100×100μm. Due to their small size, they are regarded as planar in this research. The middle part indicates the gap in the valve chamber. As the height of the gaps in the valve chambers is generally between 3 to 10μm [17], it is set to 6μm in this research.

**Figure 2.** Three-dimensional surface with different fractal dimension.

**Figure 3.** Gap model of spool and valve chamber.

**Figure 4.** The independent mesh grid of gap model.

Four gap models are established: (1) in the first model, the surfaces of the valve core and the chamber are smooth; (2) in the second one, the surface of the valve core is smooth, while the curved surface with D_s=2.1 is used as the surface of the valve chamber; (3) as for the third model, the fractal dimension with D_s=2.1 and D_s=2.3 are applied as the surfaces of the valve core and chamber, respectively; and (4) to build the forth model, the fractal dimension with D_s=2.3 and D_s=2.5 are used as the surfaces of the valve core and the chamber, separately. Since the surface roughness of the valve cores is generally smaller than that of the valve chambers, the curved surfaces with small, and large, fractal dimensions are adopted as the surfaces of the valve cores and chambers respectively in the above models. The independent mesh grid that gives consistency and converged results is shown in Figure 4.

3. **Numerical calculation and results analysis**

The definitions of some models and conditions are illustrated as follows, before the flow field analysis is described: (1) the fluids undergo steady flow; (2) the fluids are Newtonian; (3) the fluids undergo laminar flow in the valve chambers; (4) the fluids are incompressible; and (5) wall slip is considered. As for the boundary conditions, those of the inlet and outlet are pressure-inlet and pressure-outlet states, respectively, while the inlet and outlet pressures are 10MPa and 0.1MPa, separately.
3.1. **Influence of the surface roughness of the solid walls and the viscosity-temperature characteristics on the flow characteristics of the fluids in the gaps**

Figure 5 shows the influence of the viscosity-temperature characteristics on models 1 to 3 when the slip coefficient $b$ is 0.06 μm. The temperature differences analysed are 0°C, 20°C, and 40°C respectively, and the temperature of the upper walls is higher than that of the lower walls. The ordinate and abscissa indicate the ordinate of the point in the gaps and the flow velocity of the fluids. Meanwhile, only points along the line ($50, -20, z$) are analysed here. Figure 10 shows that, when the upper and lower walls are at the same temperature, the fluid velocity in model 1 presents a symmetric parabolic distribution, while that in models 2 and 3 declines gradually from the interlayer ($Y=0$) to the two sides. On the whole, as shown in Figure 10, when the temperature difference between the upper and lower walls gradually increases, the fluid velocity in the gaps also changes: the position with the maximum velocity gradually moves upward, accompanied by a significantly increased fluid velocity at the corresponding point.

Figure 6 shows that, with an increase in the temperature difference between the upper and lower walls, the slip velocity on the walls increases accordingly. Meanwhile, the variation of the slip velocity on the upper wall is obviously greater than that on the lower wall. This is because, when temperature rises, the viscosity of the fluids decreases and as a result, fluids are more likely to slip on the walls; and the larger the temperature difference, the greater the slip velocity.

![Graphs of Model 1, Model 2, and Model 3 showing gap flow characteristics under temperature characteristics.](image)

**Figure 5.** Gap flow characteristics under the temperature characteristics.
4. Conclusion
In this paper, the flow characteristics of hydraulic oil in the gap and the wall slip is analysed. As hydraulic oil flows in the gaps, the greater the surface roughness of the solid walls, the more significant the fluctuations in the slip velocity, which gives rise to a higher, slip velocity thereafter. Consequently, fluids are more likely to slip on rougher surfaces.

The viscosity-temperature characteristics in the gaps also have influenced on flow characteristics of the hydraulic oil. With regard to the viscosity-temperature characteristics of the hydraulic oil flowing in the gaps, the following conditions are satisfied at different surface roughness of the solid walls: the larger the temperature difference between the upper and lower walls, the higher the flow velocity of the hydraulic oil in the gaps and the slip velocity on the walls. That is to say, the temperature of the walls can promote the flow velocity and wall slip in the whole flow field.

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