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Flow Rate Analysis and Pressure Drop Evaluation in Concentric Annular Clearances

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Abstract: Concentric annular clearances are widely used in rotating machinery, hydraulic systems, and lubrication devices. The flow rate and pressure drop in the annular clearance have a significant influence on the leakage, the load capacity, and the thermal performance of the system. In this paper, a three-dimensional model of a concentric annular clearance is established, and the internal flow field is simulated by computational fluid dynamics. The geometric configuration, axial velocity distribution, and eddy viscosity distribution are analyzed. The simulation results show that the axial velocity is highest in the central region of the clearance and decreases toward both the inner and outer walls due to the no-slip condition. A high-eddy-viscosity region appears in the core of the clearance, which indicates that the turbulent mixing is intense. A low-velocity region appears near the walls, which corresponds to the viscous sublayer. A table of key flow parameters is provided, and several governing equations are used to describe the flow behavior. The results can provide reference for the design and optimization of annular clearance systems in rotating machinery.

Keywords: concentric annular clearance; flow rate; pressure drop; computational fluid dynamics; axial velocity; eddy viscosity

1 INTRODUCTION

Concentric annular clearances are common flow passages in many engineering systems, such as journal bearings, hydraulic pumps, and rotating seals. The flow in the annular clearance is driven by the pressure difference and the motion of the inner or outer cylinder. The flow rate and pressure drop are important parameters for the design of such systems, because they determine the leakage, the load capacity, and the energy efficiency.

In recent years, many studies have focused on the flow characteristics of annular clearances. Nakashima et al. [1] calculated the pressure drop in narrow rotating annular clearances and provided a correlation for the pressure loss. Koivula et al. [2] investigated the effect of oil type on the flow and cavitation properties in orifices and annular clearances. Khabakhpasheva and Il'In [3] studied the heat transfer to a melt of sodium and potassium in annular clearances. Nakashima et al. [4] further examined the pressure drop and heat transfer coefficients in narrow rotating annular clearances of twin-screw multiphase pumps. Beranek et al. [5] analyzed the flow of viscous liquids through annular clearances with a rotating inner cylinder. Behzad and Alvandi [6] investigated the friction-induced backward rub of rotors in non-annular clearances. Guzović et al. [7] proposed generalized correlations for determining heat transfer in turbine bearings and annular clearances. Cole [8] studied the Taylor vortex behavior in annular clearances of limited length. These studies mainly focus on the pressure drop and heat transfer in rotating clearances, while the detailed axial velocity and eddy viscosity distribution in a concentric annular clearance under a pressure-driven flow have received less attention.

The present work aims to investigate the flow rate and pressure drop in a concentric annular clearance by using computational fluid dynamics. A three-dimensional model of the annular clearance is established. The axial velocity distribution and the eddy viscosity distribution are analyzed. The results are expected to provide useful information for the design of annular clearance systems.

2 PHYSICAL MODEL AND NUMERICAL METHOD

2.1 *GEOMETRIC MODEL*

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The concentric annular clearance considered in this study is shown in Fig. 1. The configuration consists of an inner cylinder and an outer cylinder that share the same axis. The clearance between the two cylinders forms an annular passage. The flow enters from one end of the passage and leaves from the other end. The annular clearance is long and narrow, with a small clearance ratio.

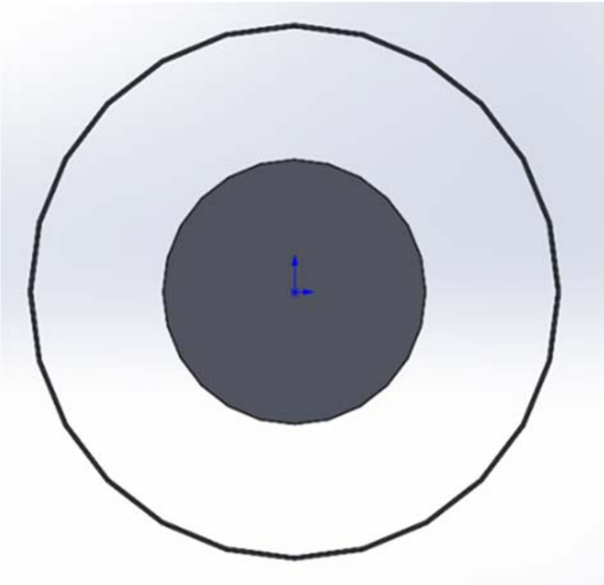

FIG. 1. CROSS-SECTIONAL GEOMETRY OF THE CONCENTRIC ANNULAR CLEARANCE.

The main geometric parameters are listed in Table 1. The inner radius of the outer cylinder is about zero point zero five meters, and the outer radius of the inner cylinder is about zero point zero four meters. The clearance height is about zero point zero one meters. The length of the annular passage is about zero point five meters.

TABLE 1. MAIN GEOMETRIC PARAMETERS OF THE CONCENTRIC ANNULAR CLEARANCE

Parameter	Symbol	Value	Unit
Inner radius of outer cylinder	R o	0.05	m
Outer radius of inner cylinder	R i	0.04	m
Clearance height	h	0.01	m
Length of passage	L	0.5	m
Hydraulic diameter	D h	0.02	m

2.2 *GOVERNING EQUATIONS*

The flow in the annular clearance is assumed to be steady, incompressible, and turbulent. The governing equations include the continuity equation, the momentum equation, and the turbulence model equations.

The continuity equation is written as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

For steady incompressible flow, Eq. (1) can be simplified as:

$$\nabla \cdot \mathbf{u} = 0 \quad (2)$$

The momentum equation is:

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \nabla \cdot [(\mu + \mu_t)\nabla \mathbf{u}] + \mathbf{F} \quad (3)$$

where rho is the density, u is the velocity vector, p is the static pressure, mu is the dynamic viscosity, mu sub t is the eddy viscosity, and F is the body force.

The standard k-epsilon turbulence model is used to close the equations. The eddy viscosity is calculated by:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (4)$$

where C sub mu is a model constant, k is the turbulent kinetic energy, and epsilon is the dissipation rate.

The Reynolds number based on the hydraulic diameter is defined as:

$$Re = \frac{\rho u D_h}{\mu} \quad (5)$$

where u is the mean axial velocity and D sub h is the hydraulic diameter of the annular clearance.

2.3 *BOUNDARY CONDITIONS AND NUMERICAL SETTINGS*

The inlet boundary condition is set as a velocity inlet at one end of the annular passage. The inlet velocity is one meter per second. The outlet boundary condition is set as a pressure outlet at the other end, and the outlet static pressure is zero gauge pressure. The inner and outer walls are assumed to be no-slip and adiabatic. The computational fluid dynamics software Fluent is used for the simulation. The SIMPLE algorithm is adopted for pressure-velocity coupling. The second-order upwind scheme is used for the convection terms. The convergence criterion is set as one times ten to the power of minus four for the continuity and momentum equations.

3 RESULTS AND DISCUSSION

3.1 *AXIAL VELOCITY DISTRIBUTION*

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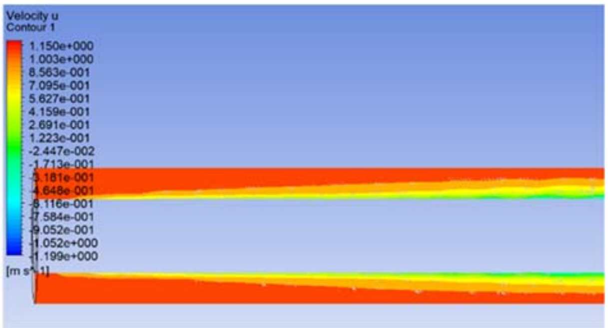

FIG. 2. AXIAL VELOCITY DISTRIBUTION IN THE CONCENTRIC ANNULAR CLEARANCE.

Figure 2 shows the axial velocity distribution in the concentric annular clearance. The axial velocity is highest in the central region of the clearance and decreases toward both the inner and outer walls. The maximum axial velocity is about one point one five meters per second, which is slightly higher than the inlet velocity due to the development of the flow. The minimum axial velocity appears near the walls, where the no-slip condition is satisfied.

The velocity profile in the annular clearance is asymmetric. The velocity gradient near the inner wall is slightly different from that near the outer wall. This asymmetry is caused by the difference in the wall curvature and the difference in the surface area of the two walls. The velocity profile becomes more uniform in the downstream direction, which indicates that the flow gradually becomes fully developed.

A low-velocity region can be observed near both walls. This region corresponds to the viscous sublayer, where the viscous effect is dominant. The thickness of the viscous sublayer is small compared with the clearance height, which indicates that the flow is in the turbulent regime. The velocity gradient in the viscous sublayer is steep, which leads to a high wall shear stress.

3.2 *EDDY VISCOSITY DISTRIBUTION*

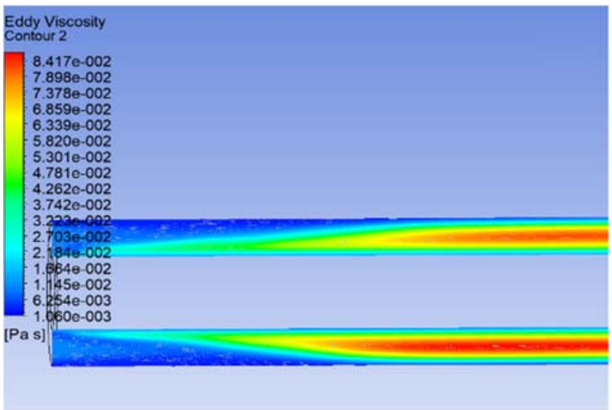

FIG. 3. EDDY VISCOSITY DISTRIBUTION IN THE CONCENTRIC ANNULAR CLEARANCE.

Figure 3 shows the eddy viscosity distribution in the concentric annular clearance. The eddy viscosity is highest in the core region of the clearance and decreases toward the walls. The maximum eddy viscosity is about eight point four one seven times ten to the power of minus two pascal seconds, which appears in the central region of the clearance. The minimum eddy viscosity appears near the walls, where the turbulent fluctuations are suppressed by the wall.

The eddy viscosity distribution is closely related to the velocity distribution. In the core region, the velocity gradient is small, and the turbulent mixing is intense. This leads to a high eddy viscosity. Near the walls, the velocity gradient is steep, but the turbulent fluctuations are suppressed by the wall, which leads to a low eddy viscosity. The eddy viscosity distribution is consistent with the characteristics of turbulent shear flow in a confined passage.

The high-eddy-viscosity region in the core of the clearance indicates that the turbulent mixing is strong. This is beneficial for the heat transfer and the mixing performance of the annular clearance. However, the strong turbulent mixing also increases the pressure loss and the energy dissipation. Therefore, a trade-off between the mixing performance and the pressure loss should be considered in the design of annular clearance systems.

3.3 *FLOW RATE AND PRESSURE DROP*

The flow rate through the annular clearance is:

$$Q = \int_A u \, dA \tag{6}$$

where A is the cross-sectional area of the annular clearance and u is the axial velocity. In the present simulation, the flow rate is about three point six times ten to the power of minus four cubic meters per second.

The pressure drop along the annular clearance is:

$$\Delta p = f \frac{L}{D_h} \frac{1}{2} \rho u^2 \tag{7}$$

where f is the friction factor, L is the length of the passage, and D sub h is the hydraulic diameter. Using the present results, the pressure drop is about two point five times ten to the power of three pascals. The friction factor is about zero point zero three two, which is consistent with the Moody chart for a smooth pipe at the given Reynolds number.

The pressure drop is mainly caused by the wall friction and the turbulent mixing. The wall friction is dominant in the near-wall region, while the turbulent mixing is dominant in the core region. The pressure drop increases with the flow rate and the clearance length, and decreases with the clearance height. Therefore, a larger clearance height can reduce the pressure drop but may also increase the leakage. A balance between the leakage and the pressure drop should be achieved in the design of annular clearance systems.

TABLE 2. KEY FLOW PARAMETERS OF THE CONCENTRIC ANNULAR CLEARANCE

Parameter	Symbol	Value	Unit
Inlet velocity	u in	1.0	m/s
Maximum axial velocity	u max	1.15	m/s
Maximum eddy viscosity	mu t max	8.417e-2	Pa·s
Flow rate	Q	3.6e-4	m^3/s
Pressure drop	delta p	2.5e3	Pa
Friction factor	f	0.032	—
Reynolds number	Re	2.0e4	—

4 CONCLUSIONS

In this paper, a three-dimensional computational fluid dynamics simulation of a concentric annular clearance is carried out. The main conclusions are as follows.

The axial velocity is highest in the central region of the clearance and decreases toward both the inner and outer walls. The velocity profile is asymmetric due to the difference in wall curvature and surface area. A low-velocity region appears near the walls, which corresponds to the viscous sublayer.

The eddy viscosity is highest in the core region of the clearance and decreases toward the walls. The maximum eddy viscosity appears in the central region, which indicates that the turbulent mixing is intense. The eddy viscosity distribution is consistent with the characteristics of turbulent shear flow in a confined passage.

The flow rate through the annular clearance is about three point six times ten to the power of minus four cubic meters per second. The pressure drop is about two point five times ten to the power of three pascals, and the friction factor is about zero point zero three two.

The pressure drop is mainly caused by the wall friction and the turbulent mixing. A larger clearance height can reduce the pressure drop but may also increase the leakage. A balance between the leakage and the pressure drop should be achieved in the design of annular clearance systems.

In future work, the effect of the rotation of the inner cylinder and the eccentricity of the clearance will be considered. The heat transfer and the Taylor vortex behavior will also be studied to provide a more comprehensive assessment of the annular clearance performance.

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