Study on Oil-Gas Separation Characteristics of Gearbox Sealing System of High-Speed Electric Multiple Unit

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Based on the discrete phase model (DPM) and droplet-wall collision model, this paper analyzes the oil-gas separation characteristic and sealing performance of a gearbox sealing system. The results show that the airflow drag force and oil droplet inertia force affect the oil-gas separation efficiency of the sealing system. Furthermore, larger oil droplet diameter leads to a higher separation efficiency and lower outlet back pressure reduces the separation efficiency of smaller diameter oil droplet and increases the separation efficiency of larger diameter droplet. For oil droplet with an intermediate diameter, the separation efficiency first decreases and then increases with the reduction in back pressure.

During the running of a high-speed electric multiple unit (EMU), the gear pair rotates at high speed and agitates the lubricating oil, therefore, a high-temperature and high-pressure environment filled with a mixed medium of lubricating oil and air forms inside the gearbox. Simultaneously, the gearbox usually adopts a non-contact labyrinth sealing structure since high-speed rotations can readily lead to the wear of sealing material. However, this type of sealing structure allows the lubricating oil inside the gearbox to easily leak through the sealing gap, resulting in insufficient internal lubrication and polluting the external environment.

Through setting a tortuous path with a complicated shape in a limited space, the non-contact labyrinth sealing structure can reduce leakage by generating extremely high flow resistance of sealing medium along the flow path. The most common form of non-contact sealing is the straight-through labyrinth seal, which has a simple structure but can cause serious ventilation effect and large leakage. A. Schaller[1] et al studied the labyrinth sealing system for a reciprocating piston compressor and analyzed the effects of cavities with different shapes and depths on the gas ventilation and sealing performance. To weaken the gas ventilation effect of a straight-through labyrinth seal, W. Zhao[2] et al proposed a bilateral straight-through labyrinth seal structure, which can improve sealing performance by adding the cavities into the stator and rotor structures. In addition, staggered[3] and stepped[4] labyrinth sealing structures have been widely applied in industrial design due to they can modify the sealing performance by disrupting the straight-through path of gas ventilation effect. Furthermore, to enhance the complexity of tortuous path, M. Alizadeh[5] et al investigated a honeycomb labyrinth sealing structure and analyzed the effects of honeycomb structures with different structural parameters on sealing performance.

An ideal gas is often used as the research medium to study labyrinth sealing structure. Meanwhile, the sealing performance of labyrinth structure is improved from the perspective of dissipating the kinetic energy of the medium. However, the medium inside gearbox is a mixture of lubricating oil and air .The aim of sealing system is to balance the differential pressure between gearbox components and reduce leakage of lubricating oil. Therefore, to study the sealing performance of labyrinth structure, the effect of sealing structure on the oil separation efficiency in the mixed medium should be considered. By enhancing the separation efficiency, the separated lubricating oil can be effectively returned to the tank through the oil-return structure, thereby reducing leakage of the lubricating oil.

Based on a DPM model and Euler-Lagrange method, L.J. Zhu[6] and K. Elsayed[7] et al analyzed the separation efficiency for particles with different diameters in a cyclone separator. It was found that the separator achieved full separation for particles larger than a critical diameter. For particles with a diameter smaller than the critical diameter, the separation efficiency can be enhanced by optimizing the pre-spin structure at the inlet and the size of inlet region. M. Farrall[8-9] et al analyzed the interaction between the oil droplet and chamber in the bearing cavity of an aero-engine. After the oil droplets collided with wall surface, they adhered to the wall forming an oil film. They also studied the variation of oil film thickness and leakage at the outlet region under different boundary conditions. X.W. Liu[10] and X. Gao[11] simulated supersonic separator and cyclone separator, respectively. Since oil droplets may not always adhere to the wall surface and sometimes rebound instead. Based on the literatures, it is necessary to consider the diverse collision results and analyze the separation efficiencies of various separators.

In this study, the gearbox sealing system of a high-speed EMU is taken as the research object. Based on the design objective of separating the lubricating oil and air, the effect of sealing system on the oil droplet separation efficiency was analyzed using the DPM and droplet-wall collision model. The sealing mechanism of the system was also investigated. Finally, the effects of different outlet back pressure and oil droplet diameter on the separation efficiency and sealing performance of the seal system were examined.

NUMERICAL MODEL

The flow of the oil-air mixture inside the gearbox sealing system is complicated. Due to the spatial restriction, a large number of vortexes are generated. Therefore, the RNG k-ε turbulence model was used to perform the numerical simulation. Considering the effects of the discrete phase (oil droplet) on the continuous phase (air), a two-way coupling analysis was adopted for calculations. The droplet-wall collision model was used to study the flow of oil droplets within the sealing system and the state of oil droplets after collision at different incident conditions was considered.

RNG *k*-*ε* model

According to renormalization group theory, turbulent flow can be considered as a transport process driven by random force. The effect of small vortexes can be simplified and merged into the eddy viscosity by spectrum analysis, which is convenient for accurately analyzing flow field distributions with high strain rates and large streamline curvatures. Equations for the turbulent energy and the turbulent energy dissipation rate of RNG *k*-*ε* model are given as follows.

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_i k)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\frac{\mu_{eff}}{\sigma_k}\bullet\frac{\partial k}{\partial x_j}\right)+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{1}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho u_i\varepsilon)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\frac{\mu_{eff}}{\sigma_\varepsilon}\bullet\frac{\partial k}{\partial x_j}\right)+c_{\varepsilon1}\frac{\varepsilon}{k}(G_k+c_{\varepsilon3}G_b)-c_{\varepsilon2}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \tag{2}$$

where G_k represents the turbulent energy generated by the average velocity gradient, G_b represents the turbulent energy generated by buoyancy, Y_m represents the expansion of compressive flow, $c_{\varepsilon1}$, $c_{\varepsilon2}$, and $c_{\varepsilon3}$ are constants, σ_k and σ_ε represent the Prandtl number of k and ε, S_k and S_ε represent the phase of the source, μ_{eff} is the effective viscosity, $\mu_{eff} = \mu + \mu_t$, in which μ is the dynamic viscosity coefficient and μ_t represents the turbulent viscosity.

Discrete Phase model

In the gearbox sealing system of a high-speed EMU, the concentration of lubricating oil in the mixture medium is very low, therefore the DPM model can be used to analyze the two-phase flow. In the DPM model, the volume fraction of discrete phase is assumed to be less than 10%, thus the effect of the discrete phase volume on the flow field can be ignored and the interaction between discrete phases are not considered. Only the coupling interaction between the discrete phase and continuous phase is considered. When analyzing the flow field in a sealing system, air is the continuous phase and lubricating oil is the discrete phase.

Under the Lagrange reference system, the motion trajectory of discrete phase can be solved using differential equations to describe the interaction between particles. In the Cartesian coordination system, the balanced differential equations for the discrete phase are given as follows.

$$\frac{du_p}{dt}=F_D\left(u-u_p\right)+\frac{g\left(\rho_p-\rho\right)}{\rho_p} \tag{3}$$

$$F_D=\frac{18\mu}{\rho_p d_p^2}\frac{C_D R_e}{24} \tag{4}$$

$$R_e=\frac{\rho d_p\left|u_p-u\right|}{\mu} \tag{5}$$

where u represents the velocity of the continuous phase, u_p represents the velocity of the discrete phase, ρ represents the density of the continuous phase, ρ_p represents the density of the discrete phase, μ represents the viscosity of the continuous phase, d_p represents the diameter of the discrete phase, F_D represents the drag force under the unit particle mass, C_D is the drag coefficient, and R_e is the Reynolds number of the discrete phase.

The velocity of particles of the discrete phase at any position can be obtained via using the equations, Eq. (3)–(5). Then, by integrating the velocity (u_p), motion trajectories of the particles were obtained.

Droplet-wall collision model

In the labyrinth sealing system, oil droplets collide with the wall surface. The motion state of oil droplet after collision determines the separation efficiency of the sealing system. C.X. Bai[12] and

D.P. Markt[13] et al pointed out that during the collision process occurring between the oil droplet and wall surface, the oil droplet loses energy. Both the magnitude and direction of the velocity of oil droplet change upon collision with the wall surface. The variation in the velocity of oil droplet depends on several factors such as the material properties, incident angle, and incident velocity, as well as the wall surface characteristics. Whether the wall surface is dry or wet also need to be considered.

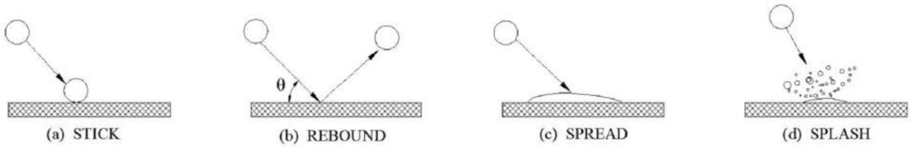

Figure 1 Schematic diagram of the collision process between an oil droplet and wall surface

Four possible cases can occur upon collision between an oil droplet and wall surface, as shown in Figure 1, which are stick, rebound, spread, and splash, respectively. After an oil droplet collides with the wall, its state is determined by the non-dimensional coefficients of droplet Weber number and Laplace number. The Weber number represents the ratio between the inertial force and surface tension and the Laplace number is the ratio between the surface tension and viscous force.

$$We = \frac{\rho_p V_n^2 d_p}{\sigma} \qquad (6)$$

$$La = \frac{\rho_p \sigma d_p}{\mu^2} \qquad (7)$$

where ρ_p represents the density of the oil droplet, μ represents the viscosity of the oil droplet, dp is the diameter of the oil droplet, σ represents the surface tension of the oil droplet, and Vn is the normal collision velocity of the droplet.

For a rebounding droplet, G. Grant[14] et al introduced the velocity-rebound coefficient e, which depends on the incident angle and can be expressed by Eq. (8) and (9).

$$e_n = 0.993 - 0.176\theta + 1.56\theta^2 - 0.49\theta^3 \qquad (8)$$

$$e_\tau = 0.988 - 1.66\theta + 2.11\theta^2 - 0.67\theta^3 \qquad (9)$$

where e_n and e_τ are the rebound coefficients in the normal and tangential directions, respectively, and θ represents the incident angle.

As the Weber number increases, the post-collision state of oil droplet changes as follows.

Dry wall:

Stick → Spread → Splash

For the stick and spread state, oil droplets attach to the wall surface and merge, then adhere to the wall.

Adhesion → Splash

In this case,

$$Wec = A \bullet La^{-0.18} \qquad (10)$$

where A depends on the toughness of wall surface and A is set to 4534 to describe the wall surface of sealing structure.

Wet wall:

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Stick → Rebound → Spread → Splash

For Stick →Rebound,

$$Wec \approx 1 \qquad (11)$$

For Rebound →Spread,

$$Wec \approx 5 \qquad (12)$$

Finally, for Spread →Splash,

$$Wec = 1320 \cdot La^{-0.18} \qquad (13)$$

It is almost impossible for the oil droplets to splash in the gearbox sealing system. For dry wall surface, the oil droplets adhere to the wall after collision. However, for the wet wall surface, post-collision states of stick, rebound, and spread may occur. Therefore, to analyze the gearbox sealing system and the collisions between oil droplet and wall surface, the dry wall surface can be ignored and all wall surfaces are considered to be wet.

Experimental Validation

In order to verify the accuracy of the proposed DPM model and droplet-wall collision model, numerical analysis was performed on the labyrinth oil-gas separator within a diesel engine valve chamber cover. The labyrinth-type separator with baffle (LTB) structure was selected to analyze the separation efficiency of the oil-air separator under different oil droplet diameters at an inlet velocity of 0.6 m/s. An oil-gas separation efficiency test bench is used to obtain the mass of oil droplet at the inlet and outlet of the cover per unit time, and then the mass of collected oil droplet is gained. Subsequently, the separation efficiency is defined as the ratio of the collected oil droplet mass relative to the entered mass. The details of LTB structure, experimental method and physical properties of the lubricating oil and air were defined as previously described in the reference 15.

Table 1 shows the separation efficiencies obtained by numerical calculation or experimental tests for different oil droplet diameters. It can be seen that a maximum error is less than 5%, suggesting the DPM model and droplet-wall collision model are suitable for performing flow field analysis of the labyrinth separator, and the calculated results are credible.

Table 1 Oil-gas separation efficiency

Oil diameter (μm)	Simulation results (%)	Test results (%)	Error (%)
3	64.8	68	3.2
5	69.1	72	2.9
10	73.9	78	4.1

PHYSICAL MODEL AND BOUNDARY CONDITIONS

Geometry model

The gearbox sealing system of a high-speed EMU consists of a labyrinth seal structure and an oil-return structure. By comparison with the real sealing system, the chamfer structure was ignored in this study, as shown in Figure 2. The labyrinth seal structure is comprised of an axial bilateral straight-through labyrinth seal and radial plug-in labyrinth seal. From the inlet to outlet, the rotor and stator structures are made up of four cavities in the axial sealing structure, referred to as cavities *I–IV*. To increase the flow resistance of the mixture medium and the probability of collision between the oil droplets and wall surface within the limited space, a radial plug-in labyrinth seal was installed between cavities *III* and *IV*, which can enhance the separation efficiency of oil-gas and improve sealing performance.

The bottom of sealing structure was equipped with a two-stage oil-return structure. The oil-return structure has two main functions: First, the presence of outlet pressure in the oil-return structure and the pressure differences inside the sealing structure, affect the pressure distribution in local area; Second, upon colliding with the wall surface of sealing structure, some oil droplets adhere to the wall surface and flow towards the bottom of the sealing structure under the gravity force, then flow to the oil pool inside the gearbox via the oil-return structure, thereby accomplishing the oil-return process.

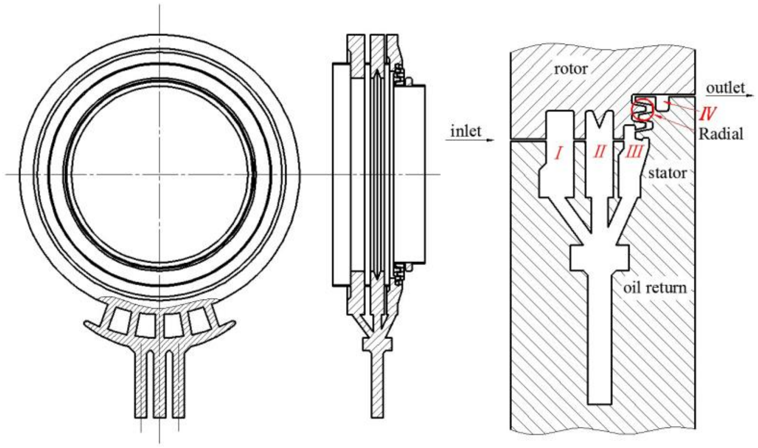

Figure 2 Schematic diagram of sealing system

Boundary conditions

When the inlet and outlet pressures of the sealing system and the amount of leakage are stable, the internal flow field can be recognized as three-dimensional steady flow. The inlet pressure of sealing structure was set to 500 Pa, and the outlet was set as the ambient back pressure of -500 Pa. The outlet pressure of oil-return structure was determined by the internal pressure of oil pool inside the gearbox and sets to 200 Pa. The rotor speed was set to 3000 r/min. The lubrication oil used in the gearbox was 75W-90 grade gearbox oil. In the calculations, the diameter of oil droplets was in the range of 0.5 -10μm, the density of oil was 843 kg/m^3, and the viscosity was set to 16.6 mm^2/s.

In the DPM model, air was the continuous phase and the lubricant oil was the discrete phase. The inlet and outlet of sealing structure and the outlet of oil-return structure were considered to be escape. Therefore, the oil droplets escaped from the sealing structure were not included in subsequent calculations. The wall surface of sealing system adopted a User Defined Function by FLUENT. According to the collision condition of the oil droplets and wall surface and the droplet-wall collision model, DEFINE_DPM_BC was compiled. If the Weber number of incident oil droplet ranges from 1 to 5, the oil droplet rebounds according to Eq. (8) and Eq. (9), and then enters into the flow field to participate in the subsequent calculation. When the Weber number is less than 1 or greater than 5, the oil droplet adhered to the wall surface is recognized as a trapped droplet, which is excluded in subsequent calculations.

The sealing performance of gearbox sealing system depends on the oil-gas separation efficiency. In our analysis, oil droplets trapped by the wall were assumed to return to the oil pool through the oil-return structure. The trapped oil droplets escaped from the wall surface and entered into the flow field under airflow force and gravity were not in our consideration. The oil-gas separation efficiency was calculated as follows:

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$$\eta = \left(1 - \frac{m_{outescape}}{m_{all}}\right) \times 100\% \qquad (14)$$

where $m_{outescape}$ is the mass of the oil droplets that have escaped from the sealing structure and mall represents the mass of all droplets entering the sealing system.

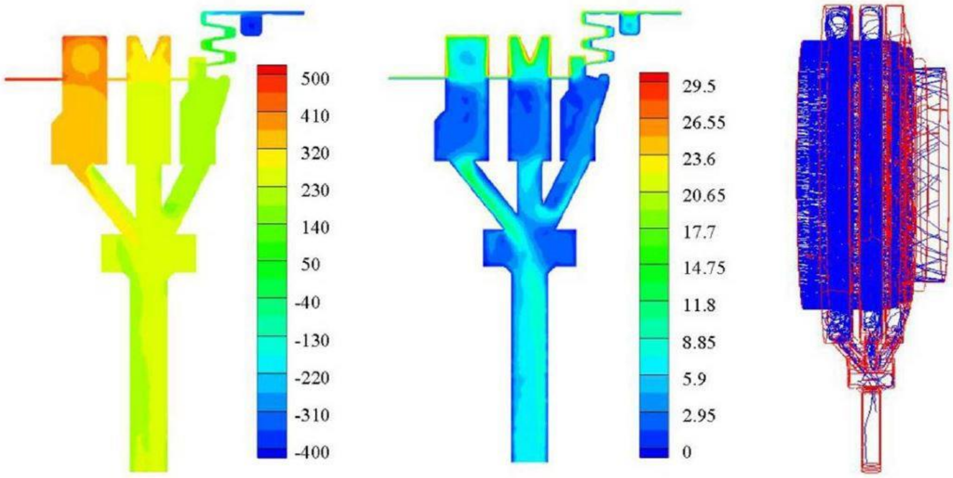
Grid independency

A necessary prerequisite for the simulation calculations is to set an appropriate mesh size since the mesh density affects the simulation accuracy and efficiency. The gearbox sealing system was partitioned by an unstructured grid and a standard wall function was adopted for the wall surface to allow local refinement for areas such as sealing gaps. Five grids with different densities are employed to study the grid independency including the cell number ranging from 0.51 million to 1.82 million and oil-gas separation efficiency is used as the characteristic parameter. As the grid number increases from 0.51 million to 1.3 million, the oil-gas separation efficiency decreases. However, the separation efficiency trends to be stable as the grid number ranging from 1.3 million to 1.82 million. Taking both the calculation accuracy and efficiency into consideration, a discrete model with a grid number of 1.53 million is selected for the subsequent simulation.

RESULTS AND DISCUSSION

Flow field in sealing system

The flow field distribution inside the gearbox sealing system of a high-speed EMU significantly influences the motion of oil droplets. Numerical calculations were performed to analyze the internal flow field of the sealing system for an oil droplet with a diameter of 3μm. The pressure cloud map, velocity cloud map, and motion trajectory of the oil droplets are shown in Figure 3.



(a) Cloud map of pressure (b) Cloud map of velocity (c) Trajectory of oil droplets

Figure 3 Flow field distribution inside the sealing system

As shown in Figure 3 (a) and (b), the medium enters the sealing structure from the inlet, forming a strong vortex inside the cavity and dissipating the energy due to the jet action of the sealing tooth and due to the limitations of the cavity structures. Finally, the outlet back pressure is affected and a pressure drop is achieved. The presence of the oil-return structure changes the pressure distribution and velocity distribution of the sealed stator cavity. As a result, the stator cavity not only needs to account for the pressure drop of the sealing structure, but also needs to balance

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the outlet pressure drop of the oil-return structure. Therefore, the pressure gradient and velocity of oil-return corresponding to cavity *I* are significantly larger than those of cavities *II* and *III*.

It can be observed in Figure 3 (c) that oil droplets are injected from the inlet into the cavity in a rotating state. Most oil droplets are captured by the wall surface of sealing system and oil-return structure. A small proportion of oil droplets rotates with the airflow and escapes out of the sealing system after passing through the sealing outlet and oil-return outlet. During the collision process between oil droplets and wall surface, the number of oil droplets captured by cavity *I* and its corresponding oil-return structure is significantly larger than those captured by cavities *II* and *III*. This is consistent with the phenomenon that the oil droplets have a larger pressure gradient and velocity in cavity *I*. Therefore, in the structural design of the system, the capture of oil droplets by cavity I and its corresponding oil-return structure need to be preferential guaranteed, which can enhance the oil-gas separation efficiency of the sealing system.

Along with the airflow, oil droplets enter into the sealing system from the inlet at a certain speed. Under the drag force generated by airflow, a proportion of the oil droplets flows out from the outlet within the airflow leading to the leakage of oil droplets, and thereby reducing the separation efficiency of sealing system. In contrast, some oil droplets inertial force can overcome the airflow drag force with the assistance of vortex and sealing gap, making them cannot rapidly change flow direction within the airflow. This results in the collisions between the oil droplets and wall surface, which increase the probability of oil droplet captured by wall surface and enhances the separation efficiency of the system. These two effects are called the airflow drag effect and the oil droplets inertia effect. The separation efficiency of the system depends on the combined effects of drag forces and inertial forces. Less drag and greater inertia lead to a higher separation efficiency and improve sealing performance.

Effect of oil droplet diameter

The diameter of an oil droplet determines its volume and mass, which effects the inertia of oil droplet and the separation efficiency of sealing system. In order to analyze the effect of droplet diameter on the oil-gas separation efficiency and sealing performance, separation efficiencies of the gearbox sealing system were calculated for a droplet diameter ranging of 0.5μm -10μm. All other conditions were held constant. Separation efficiency curves of the sealing system for different droplet diameters are shown in Figure 4.

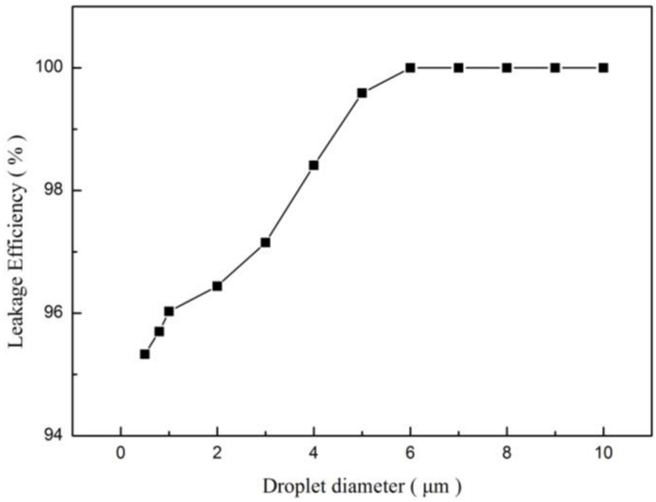

Figure 4 Relationship between separation efficiency and droplet diameter

As seen from Figure 4, as the diameter of oil droplets increases, the separation efficiency of sealing system increases gradually. When the oil droplet diameter in range of 0.5μm - 5μm, the separation efficiency increases near-linearly with the increase of droplet diameter. When the diameter

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ranges from 5μm to 6μm, the increasing trend in separation efficiency slows down. While for the oil droplet diameter exceeds 6μm, the separation efficiency is 100%, suggesting that under the boundary conditions, the sealing system captures all the oil droplets with a diameter greater than 6μm.

The droplet with small diameter has a smaller volume and mass resulting in a strong drag force of the airflow. Thus, the oil droplet can change direction quickly to follow the airflow, avoiding structures such as the sealing teeth more effectively and reducing the probability of collision with the wall surface. Consequently, a low separation efficiency is achieved. In the case of oil droplets with larger diameters, the masses of oil droplets increase and then the oil droplets are accelerated by structures like the sealing teeth. The oil droplets inertia force also increases, which enhances the probability of collision with the wall surface and the probability of oil droplet trapped by the wall surface, resulting in a higher separation efficiency. Under the present boundary conditions of sealing structure, when the diameter of oil droplet exceeds 6μm, the oil droplets inertial force is much stronger than the airflow drag force, which eventually causes the oil droplets to be fully captured by the wall surface, thus complete separation of the mixture medium is accomplished.

Effect of outlet back pressure

When the inlet pressure of sealing structure and outlet pressure of oil-return structure are predefined, changes in the outlet back pressure can affect the pressure gradient of internal flow field, thereby the separation efficiency of sealing system is affected. During the running of the EMU, the outlet back pressure is determined by the gearbox external structure and operation factors such as train speed, the pressure wave of crossing-train and tunnel. In order to analyze the effects of outlet back pressure on the oil-gas separation efficiency and sealing performance of the sealing system, separation efficiencies of the sealing system were calculated under back pressures ranging from 0 to -1500 Pa. All other boundary conditions were held constant. The separation efficiency-outlet back pressure curves for droplets of different diameters are presented in Figure 5.

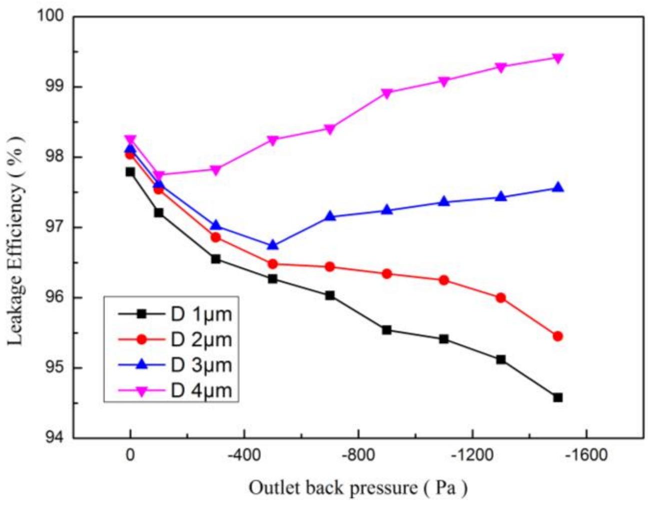

Figure 5 Relationship between separation efficiency and outlet back pressure

It can be seen from Figure 5 that the effects of the outlet back pressure on separation efficiency of the sealing system are different for different droplet diameters: When the oil droplet diameter is between 1μm and 2μm, the separation efficiency of sealing system gradually decreases as the back pressure decreases. The separation efficiency is greatly reduced in the oil droplet with diameter of 1μm. While for the oil droplet diameter ranging from 3μm to 4μm, the separation efficiency first decreases and then increases with decreasing back pressure. For the oil droplet with diameter of 4μm, the back pressure at the inflection point of separation efficiency is -100 Pa, while for 3 μm oil droplet, the pressure decreases to -500 Pa.

Under constant inlet and outlet pressure of the oil-return structure, when the outlet back pressure decreases, the increased negative pressure outside the sealing system accelerates the flow of the internal oil-gas mixture. When the diameter of oil droplet is small, drag of the airflow will dominate. Therefore, the back pressure decreases as the oil droplet velocity increases, which shortens the residence time in the sealing system and causes the oil droplets to flow out of the sealing system quickly, resulting in a lower separation efficiency. When the diameter of oil droplet is larger, the inertial force plays a dominate role. Therefore, the decreasing back pressure accelerates the oil droplets and causes them to collide with the wall surface, which increases the efficiency of capture and thus increases the separation efficiency of sealing system. The larger the diameter, the smaller the airflow drag effect, and the greater the oil droplets inertial effect. As a result, the reduction in back pressure decreases the separation efficiency for oil droplets with small diameters, increases the separation efficiency of oil droplets with large diameter, and first decreases then increases the separation efficiency of oil droplets with intermediate diameters.

CONCLUSION

The lubricating oil and air separation efficiency of the gearbox sealing system of a high-speed EMU determines the overall performance of sealing system. To improve the design of the oil-gas separation chamber, the DPM and droplet-wall collision model were adopted to analyze the performance of sealing system. The effects of different oil droplet diameters and outlet back pressures on the separation efficiency of sealing system were investigated and the main conclusions are shown below.

Within the gearbox sealing system, the parameters of cavity *I* is critical for the oil-gas separation efficiency. Therefore, in order to enhance the oil-gas separation efficiency, the capture of oil droplets by cavity *I* and its corresponding oil-return structure should be preferentially guaranteed in the structural design for the sealing system.

The dominant factors affecting oil-gas separation efficiency are the airflow drag effect and the oil droplets inertial effect. The greater the drag forces acting on the oil droplets, the weaker the inertial effects, and therefore, the lower the separation efficiency of sealing system. Consequently, poor sealing performance is obtained.

The larger the oil droplet diameter, the higher the separation efficiency of sealing system. Oil droplets with small diameters are mainly dragged by the airflow whereas oil droplets with large diameters are mostly affected by inertial forces.

The effect of outlet back pressure on the oil-gas separation efficiency of sealing system is closely related to the oil droplet diameter. When the back pressure decreases, the separation efficiency of small droplets is reduced, the separation efficiency of large droplets increases, and the separation efficiency of intermediate diameter oil droplets first decreases then increases.

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