

Article

Research on Oil–Gas Two-Phase Flow Characteristics and Improvement of Aero-Engine Bearing Chamber

Guozhe Ren, Yanpeng Li, Huan Zhao *, Yang Yan, Wenfeng Xu  and Dan Sun

Liaoning Key Lab of Advanced Test Technology for Aerospace Propulsion System, Shenyang Aerospace University, Shenyang 110136, China; renguozhe7917@163.com (G.R.); lianpeng1998@163.com (Y.L.); 18840620443@163.com (Y.Y.); xuwf789@163.com (W.X.); phd_sundan@163.com (D.S.)

* Correspondence: phd_zhaohuan@163.com

Abstract: In order to study the oil–gas two-phase flow characteristics of an aero-engine bearing chamber and improve the scavenge effect of lubricating oil, the two-phase flow solution model of a bearing chamber based on the Euler–Euler method was established. Three improvement schemes were proposed for the ventilation structure and scavenge structure of the bearing chamber. The flow characteristics and scavenge characteristics of a conventional bearing chamber and three improvement schemes under different working conditions were analyzed in depth. The results show that after the conventional bearing chamber ventilation structure is embedded (Embed) and improved, with the increase in the embedding depth, the oil in the cavity is further blocked in the cavity, the amount of oil flowing out from the vent is further reduced, and the scavenge efficiency is further improved. After the slope improvement of the scavenge structure of the conventional bearing chamber, due to the increase in the depth of the oil return groove, the drag effect of the air shear force in the cavity on the oil in the oil return groove is further weakened, and the oil accumulation area on the right side of the scavenge port is further suppressed. The volume fraction of the oil in the cavity is further reduced, and the scavenge efficiency is further improved. The combined improvement scheme (ES) can take into account the advantages of embedding and slope improvement schemes, and further improve the scavenge efficiency. Compared to the conventional bearing chamber, when the oil flow rate is 200 L/h and the speed is 15,000 r/min, the oil return efficiency of the embedded ($h = 12$ mm), slope ($l = 56$ mm) and combined improvement schemes are increased by 20.19%, 13.43%, and 37.94%, respectively.

Keywords: aero-engine; oil–gas two-phase; bearing cavity; ventilating structure; scavenge structure; scavenge efficiency



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1. Introduction

When the aero-engine lubricating oil system is working, the lubricating oil enters the bearing cavity through the lubricating oil nozzle. Under the action of centrifugal force, the lubricating oil with cooling and lubricating effects is atomized into tiny lubricating oil particles. The interaction between oil and air forms a complex oil–air two-phase flow in the bearing chamber. A large number of studies have shown that it is of great significance to carry out research on the characteristics and improvement of oil–air two-phase flow in the bearing chamber of aero-engine [1–3].

The flow characteristics of lubricating oil in the bearing chamber have been studied in depth at home and abroad. Wiet et al. [4] and Aidarinis et al. [5] have pointed out that the oil in the bearing chamber will break into droplets after interacting with the high-speed air flow. The oil droplets flow to the scavenge port under the action of gravity and accumulate at the scavenge port. The accumulation of lubricating oil at the scavenge port will lead to the decrease in the scavenge efficiency of the bearing chamber and affect the effective utilization rate of the lubricating oil. In China, Chen Guoding et al. [6–9] proposed an analysis method for oil droplet deposition characteristics, oil film flow characteristics and energy transfer

between oil droplet phase and air in the bearing chamber, which provides a reference for lubrication and heat transfer design of the bearing chamber. Lu et al. [10] used the Hilbert–Huang transform method to analyze the spectral characteristics of the pressure signal in the bearing chamber, established the correlation between the energy index and the flow pattern, and obtained the distribution law of the oil on the wall. However, the aforementioned studies lack detailed research on the position of lubricating oil accumulation in the bearing chamber. Zhao et al. [11] studied the oil–gas two-phase flow in a common bearing chamber and obtained the change rule of lubricating oil accumulation and rotational speed. The results show that when the flow rate is large, the lubricating oil is easy to accumulate on the side of the rotation direction of the scavenge port at low speed; at high speed, the shear force overcomes the influence of gravity, and the distribution of lubricating oil on the inner wall of the bearing chamber is more uniform.

In order to reduce the retention of oil in the bearing chamber and improve the oil return characteristics of the bearing chamber, Simmons et al. [12] adjusted the position of the scavenge port to slip. Chandra et al. [13–15] added the oil return groove structure at the scavenge port and analyzed the influence of different oil return groove depths on the oil return characteristics of the bearing chamber. The research results show that the oil return groove can weaken the drag of the air flow in the chamber to the lubricating oil to a certain extent, and then effectively guide the lubricating oil to flow out from the scavenge port, reduce the volume fraction of the lubricating oil in the chamber, and improve the scavenge efficiency. When the depth of the oil return groove increases, the scavenge efficiency of the bearing chamber increases more obviously. In order to reduce the amount of oil carried by the airflow in the chamber, Kurz et al. [16,17] and Chandra et al. [18–20] added cover plates or porous grid plates and other auxiliary materials at the inlet of the oil return tank. The test results show that the auxiliary materials increase the proportion of oil flowing out from the scavenge port, the volume fraction of oil in the chamber is significantly reduced, the oil retention is reduced by 18% and the scavenge efficiency is significantly improved. Matthias et al. [21] pointed out that the distribution of lubricating oil in the bearing chamber is not uniform, and the lubricating oil in the bearing chamber is mainly distributed on the oil return groove and the outer wall of the bearing chamber. Due to the dual effects of air shear force and gravity, the oil film is thinner in the area where the shear force component and the gravity direction are consistent near the oil return groove. Therefore, according to the distribution position of lubricating oil, improving the structure of the outer wall of the bearing chamber to a certain extent can effectively reduce the retention of lubricating oil in the chamber, and then improve the oil return characteristics of the bearing chamber. In addition, the amount of lubricating oil flying out from the vent cannot be ignored. Farrald et al. [22] pointed out that when the speed is high, the amount of lubricating oil flowing out from the vent is as high as 12%, which seriously affects the effective utilization of lubricating oil.

At present, in the published literature, most of the research on the improvement of bearing chamber structures is focused on experimental research, and most of the improvement is limited to the oil return structure; there is little research on the ventilation structure. At the same time, there is little analysis of the oil–gas two-phase flow characteristics inside the bearing chamber. Therefore, this paper first improves the ventilation structure and oil return structure of the bearing chamber separately.

2. Numerical Method

2.1. Control Equation of Two-Phase Flow in Bearing Chamber

The research object of this paper is the oil–gas two-phase flow field structure of the bearing chamber. The air phase is the main phase and the lubricating oil phase is the secondary phase. A large number of studies have shown that the Euler–Euler multiphase flow model has complete global information in the particle phase and is suitable for large-scale volume fraction flow. The turbulence factor can be automatically included in the model calculation process. Compared with other turbulence models, the computational

cost is relatively low [23–25]. Therefore, in this paper, the Euler–Euler heterogeneous multiphase flow model is used to solve the complex oil–gas two-phase flow field structure in the bearing chamber.

1. Two-phase flow mixture model

The mixing model is a two-phase flow model for phase α and phase β . The surface area per unit volume is:

$$A_{\alpha\beta} = \frac{\gamma_{\alpha} \cdot \gamma_{\beta}}{d_{\alpha\beta}} \quad (1)$$

In the formula, γ is the volume fraction of the phase, and $d_{\alpha\beta}$ is the interface length scale.

2. Continuity equation

$$\frac{\partial}{\partial t}(\rho_{\alpha} u_{\alpha}) + \nabla \cdot (\rho_{\alpha} u_{\alpha} u_{\alpha}) = S_{MS\alpha} + \sum_{\beta=1}^{N_p} \Gamma_{\alpha\beta} \quad (2)$$

In the formula, ρ is the density, u is the fluid velocity and $\Gamma_{\alpha\beta}$ is the mass flow rate per unit volume from the gas phase to the liquid phase, which only occurs when interphase mass transfer occurs.

3. Momentum equation

$$\begin{aligned} \frac{\partial}{\partial t}(\gamma_{\alpha} \rho_{\alpha} u_{\alpha}) + \nabla \cdot (\gamma_{\alpha} (\rho_{\alpha} u_{\alpha} \otimes u_{\alpha})) &= \sum_{\beta=1}^{N_p} (\Gamma_{\alpha\beta}^+ u_{\beta} - \Gamma_{\beta\alpha}^+ u_{\alpha}) + \\ \nabla \cdot (\gamma_{\alpha} u_{\alpha} (\nabla u_{\alpha} + (\nabla u_{\alpha})^T)) &+ S_{M\alpha} + M_{\alpha} - \gamma_{\alpha} \cdot \nabla P_{\alpha} \end{aligned} \quad (3)$$

In the formula, $S_{M\alpha}$ describes the momentum source caused by external force; M_{α} describes the interfacial force acting on phase α due to the presence of other phases.

4. Energy equation

The total energy equation of multiphase flow is extended on the basis of the single-phase total energy equation, and the following total energy equation is obtained:

$$\frac{\partial(\rho h_{tot})}{\partial t} - \frac{\partial p}{\partial t} + \nabla \cdot (\rho u h_{tot}) = \nabla \cdot (\lambda \nabla T) + \nabla \cdot (u \cdot \tau) + u \cdot S_M + S_E \quad (4)$$

$$h_{tot} = h_{stat} + \frac{1}{2}(u \cdot u) \quad (5)$$

In the formula, λ is the thermal conductivity, τ is the shearing force, h_{tot} is the total enthalpy, h_{stat} is the static enthalpy, S_M is the momentum source and S_E is the energy sources.

5. Turbulent flow model

The flow equation of SST k - ω is:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\Gamma_{\omega} \frac{\partial k}{\partial x_j} \right] + G_k - Y_k + S_k \quad (6)$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho \omega u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\Gamma_{\omega} \frac{\partial \omega}{\partial x_j} \right] + G_{\omega} - Y_{\omega} + D_{\omega} + S_{\omega} \quad (7)$$

In the formula, G_k and G_{ω} represent the production terms of k and ω , respectively; Γ_k and Γ_{ω} represent the effective diffusion coefficients of turbulent kinetic energy k and specific dissipation rate ω , respectively; Y_k and Y_{ω} represent the dissipation terms of k and ω , respectively. D_{ω} is the cross-diffusion term. The details are shown in Reference [26].

2.2. Geometric Structure of Bearing Cavity

The typical aero-engine bearing chamber is shown in Figure 1a. Among them, along the axial direction, one end is the oil inlet and the other end is the sealing gas inlet; in the vertical direction, the upper part of the bearing chamber is the ventilation structure, and the lower part is the oil return structure. On the basis of the original bearing chamber structure (Normal), the bearing cavity is improved, and three bearing chamber improvement schemes are obtained, namely the embedded improvement scheme (Embed), slope improvement scheme (Slope) and combined improvement scheme (ES). The detailed parameters of the three improvement schemes are shown in Table 1. The embedded improvement scheme embeds the vent into the bearing chamber, and the embedded depth is h , as shown in Figure 1b. The slope improvement scheme makes the slope transition on the right wall of the scavenge port of the bearing chamber. The slope inclination angle is 45° , and the depth of the oil return groove is l , as shown in Figure 1c. The combined improvement scheme is embedded improvement and slope improvement in the ventilation structure and the oil return structure, respectively, as shown in Figure 1d.

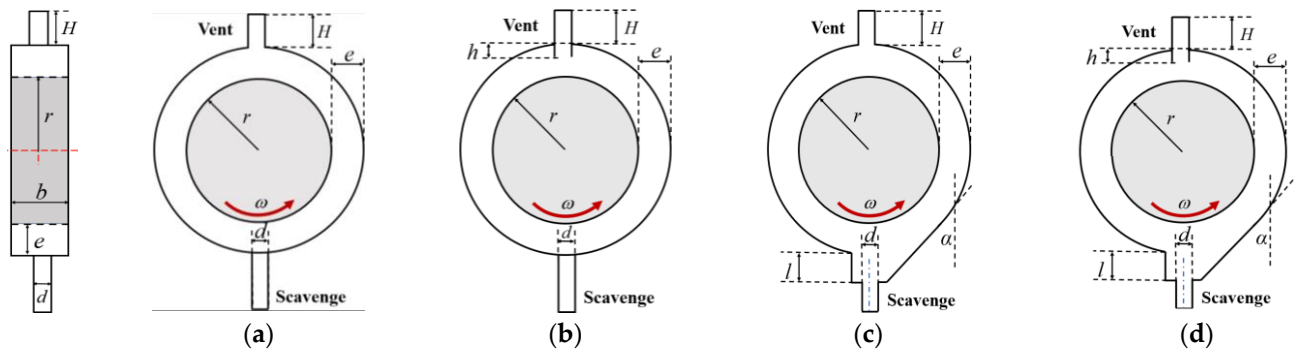


Figure 1. Geometric mechanism of the bearing chamber. (a) Normal; (b) Embed; (c) Slope; (d) ES.

Table 1. Geometric parameters of bearing chamber.

Parameter	Normal	Embed	Slope	ES
Rotation radius r /(mm)	72	72	72	72
Height e /(mm)	32	32	32	32
Width b /(mm)	48	48	48	48
Port diameter d /(mm)	36	36	36	36
Tangential angle α /($^\circ$)	0	0	45	45
Inlet height H /(mm)	16	16	16	16

2.3. Mesh and Boundary Conditions

In this paper, ANSYS Meshing software is used to mesh the geometric model of the fluid domain of the conventional bearing chamber and the bearing chamber of different improvement schemes. The unstructured mesh with a size of 2 mm is used, and the mesh encryption of the oil supply port, the vent and the return port is carried out. Finally, the number of fluid domain meshes in the conventional bearing chamber is determined to be 3.2 million; the number of meshes in the fluid domain of the bearing chamber with vent embedded depth $h = 8$ mm, $h = 10$ mm and $h = 12$ mm is 3.4 million, 3.49 million and 3.56 million, respectively. The depth of the oil return groove is $l = 40$ mm, $l = 48$ mm and $l = 56$ mm. The number of fluid domain grids in the bearing chamber are 3.35 million, 3.51 million and 3.69 million, respectively. The number of fluid domain meshes in the bearing chamber of the combined scheme is 3.9 million.

In this paper, the unstructured mesh is used to divide the computational domain mesh, and the mesh encryption is carried out at the oil and air inlets, respectively, as shown in Figure 2. The inlet boundary of air and lubricating oil is set as the mass flow boundary, the vent and scavenge port are set as the pressure boundary, and the pressure boundary

is set as the pressure value of 0.12 MPa. The mass flow rate of the air inlet is 10 g/s, and the mass flow rates of the oil inlet are 200 L/h, 600 L/h and 1000 L/h, respectively. The oil inlet temperature and air inlet temperature are 373.15 K. The incident tangential velocity of lubricating oil is half of the rotating shaft velocity. The given oil density is 912 kg/m^3 and the dynamic viscosity is $0.0045 \text{ kg/m}\cdot\text{s}$.

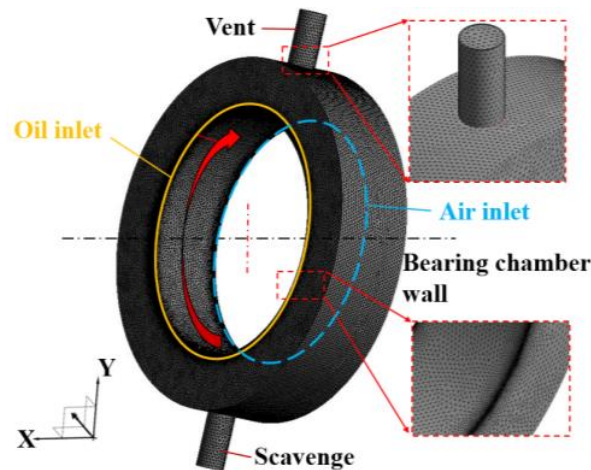


Figure 2. Mesh structure of bearing chamber.

2.4. Accuracy Verification of Numerical Method

In order to verify the reliability of the numerical method used in this paper, the bearing chamber test piece of Karlsruhe University in Germany [27] shown in Figure 3 is selected as the research object, and the accuracy of the numerical method in this paper is verified by the test results of the test piece.

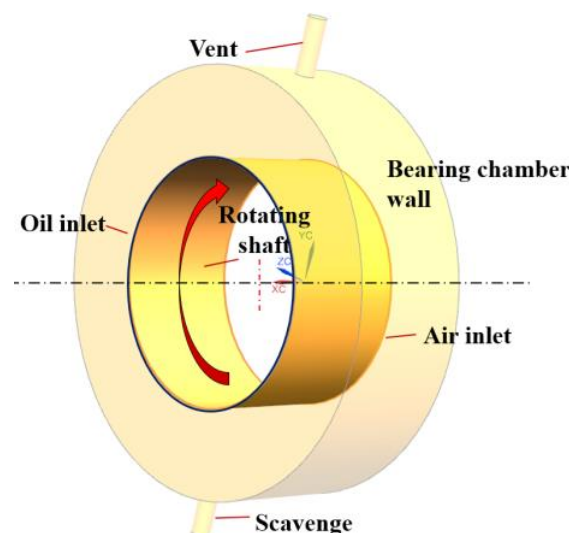


Figure 3. Karlsruhe University bearing chamber calculation model.

In this paper, an experimental cavity in the bearing chamber test piece from Karlsruhe University in Germany is taken as the research object. The air and oil boundaries are set as the mass flow boundary, and the vent and scavenge boundaries are the pressure boundary. Ensure that the air inlet flow, oil inlet flow, vent and scavenge pressure conditions remain unchanged, change the speed to verify the accuracy. The specific geometric parameters are shown in Table 2:

Table 2. Geometric parameters of the bearing chamber.

Structure	Parameter	Structure	Parameter
Rotation radius $r_{sh}/(\text{mm})$	62	Height of bearing cavity $h_1/(\text{mm})$	28
Bearing cavity width $b/(\text{mm})$	46	Diameter of vent $d/(\text{mm})$	17
Diameter of scavenge $d/(\text{mm})$	17	Height of vent $h_2/(\text{mm})$	40
Height of scavenge $h_2/(\text{mm})$	40		

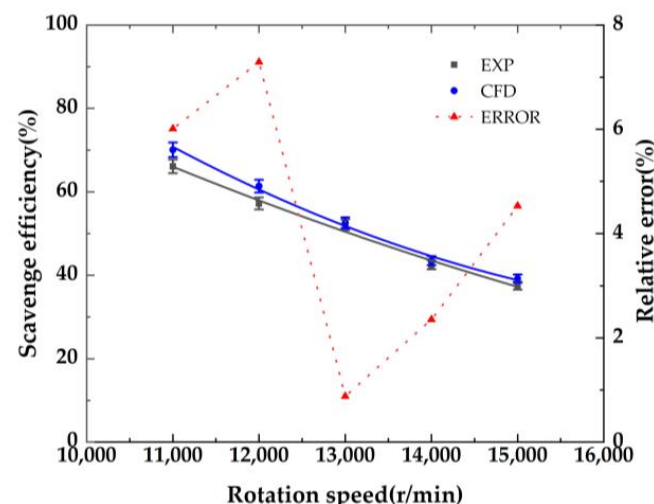
At the same time, in order to quantitatively evaluate the oil return characteristics of the bearing chamber, according to the literature [11], the scavenge efficiency formula is defined as follows:

$$\eta_{sc} = \frac{q_{v,oil,sc}}{q_{v,oil,out}} = \frac{q_{v,oil,sc}}{q_{v,oil,sc} + q_{v,oil,vt}} \quad (8)$$

$$q = \frac{1}{t} \int_{t_0}^{t_0+t} m dt \quad (9)$$

In the formula, $q_{v,oil,sc}$ denotes the oil flow from the scavenge, unit: g/s; $q_{v,oil,vt}$ represents the oil flow from the vent, unit: g/s; m represents unit mass flow, unit: g/s; t represents time, unit: s.

Figure 4 is the comparison between the numerical simulation results and the experimental values in reference [27]. From the diagram, it can be seen that with the increase in the rotational speed, the scavenge efficiency decreases. This is because after the rotational speed increases, the shear force of the air in the cavity on the oil increases, and the ability of the oil to overcome the gravity increases. Due to the drag of the air in the cavity, the amount of oil flowing out from the vent increases, which leads to a decrease in the oil return efficiency. By comparison, it is found that the numerical simulation results are basically consistent with the experimental values. Among them, the error of the low-speed condition is relatively large, and the error of the high-speed condition is relatively small. The error of each speed is below 5%, the maximum error is 12,000 r/min, the error is 4.91%, the minimum error is 13,000 r/min, and the error is 0.88%, which further proves that the numerical method in this paper is reliable.

**Figure 4.** Comparison of calculated and experimental values of oil return efficiency.

3. Analysis of Two-Phase Flow Field Characteristics

3.1. Analysis of Calculation Results of Embedded Improvement Scheme

In this section, three embedding depths are proposed for the embedding improvement scheme, namely $h = 8$ mm, $h = 10$ mm and $h = 12$ mm. The numerical simulation of the oil–gas two-phase flow field structure of different embedded improvement schemes is

carried out to obtain the mechanism of the embedded improvement scheme on the oil–gas two-phase flow field structure inside the bearing chamber, which provides a reference for the improvement of the conventional bearing chamber.

3.1.1. Leakage Analysis

The oil leakage of the embedded improvement scheme is shown in Figure 5. Among them, the blue area is the amount of oil flowing from the vent, and the yellow area is the amount of oil flowing from the scavenge. From the diagram, it can be seen that when the speed is the same, with the increase in the oil flow rate, the oil flow rate of each bearing chamber scheme from the vent and the scavenge port is significantly increased. When the oil flow rate is 200 L/h, the oil flow from the vent of the conventional bearing chamber increases with the increase in the rotational speed, and the oil flow from the return port decreases with the increase in the rotational speed. This is because the oil flow is relatively small at this time, and the effect of gravity is relatively small. After the rotation speed increases, the shear force of the air in the cavity increases, and the drag effect on the oil is more significant. More oil is carried out of the bearing chamber by the air from the vent, which leads to a decrease in the amount of oil flowing out of the oil return port. When the oil flow rate is 200 L/h, the change rule of the oil flow from the vent and the scavenge with the number of revolutions is obviously different from that of the conventional bearing chamber. At this time, with the increase in the rotational speed, the oil flow from the vent of the embedded improvement scheme increases first and then decreases, and the oil flow from the scavenge decreases first and then increases. When the amount of oil is 1000 L/h, with the increase in rotational speed, the amount of oil flowing out of each bearing chamber from the vent and scavenge has few changes.

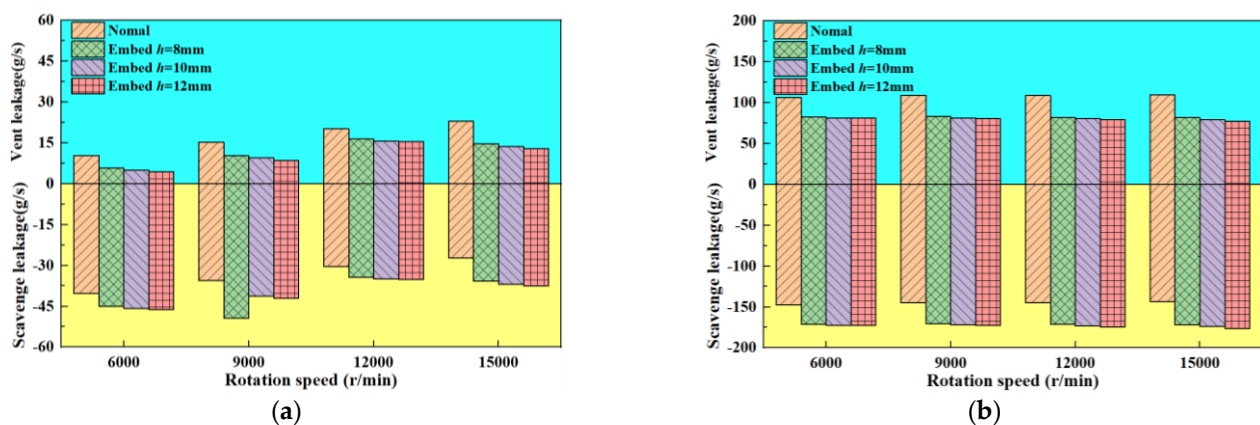


Figure 5. Comparison chart of oil leakage. (a) 200 L/h; (b) 1000 L/h.

Through comparison, it is found that when the oil flow rate and rotational speed are the same, compared with the conventional bearing chamber, the amount of oil flowing out from the vent of the embedded improvement scheme is significantly reduced, and the amount of oil flowing out from the scavenge port is significantly increased. At the same time, with the increase in embedding depth, the amount of oil flowing out from the vent is further reduced, and the amount of oil flowing out from the scavenge port is further increased. This is because after the embedding depth increases, the embedded vent wall can further block the lubricating oil in the cavity, effectively inhibiting the outflow of lubricating oil from the vent—thereby allowing more lubricating oil to flow out from the return oil—and increasing the leakage of the scavenge. Compared with the conventional bearing chamber, when the speed is 9000 r/min, the oil flow rates are 200 L/h and 1000 L/h, respectively; the oil flow from the vent of the embedded improvement scheme $h = 12$ mm is reduced by 6.67 g/s and 28.27 g/s, respectively; and the oil flow from the return port is increased by 6.61 g/s and 27.73 g/s, respectively. When the speed is 15,000 r/min and the oil flow is 200 L/h and 1000 L/h, respectively, the amount of oil flowing out of the vent is

reduced by 10.09 g/s and 32.55 g/s, respectively, and the amount of oil flowing out of the return port is increased by 10.22 g/s and 32.57 g/s, respectively.

3.1.2. Analysis of Volume Fraction of Lubricating Oil in Cavity

In order to further explore the change law of the amount of lubricating oil flowing out from the vent and scavenge with the speed of the embedded improvement scheme, the flow field structure of the embedded improvement scheme with the oil flow rate of 200 L/h and $h = 12$ mm under different speed conditions is selected for in-depth analysis. Figure 6 is the volume fraction distribution of lubricating oil in the cavity of the embedded improvement scheme with $h = 12$ mm. From the diagram, it can be seen that the rotation direction of the bearing chamber is counterclockwise, and the gravity of the oil in the right chamber is opposite to the direction of the air shear force in the cavity, which is not conducive to the oil in the right cavity of the scavenge flowing into the scavenge. There is a large area of oil accumulation on the right side of the scavenge. At this time, the gravity effect of the oil in the accumulation area is relatively significant. Concurrently, due to the drag of air shear force, the oil in the accumulation area moves to the vent. With the increase in rotational speed, the air shear force increases, and the drag trend of air to the oil in the accumulation area on the right side of the scavenge is more significant, such as the black dotted arrow. In addition, there is also a phenomenon of oil accumulation on the left side of the vent of the embedded improvement scheme, such as the black dotted line. Embedding the wall to block the oil in the cavity is the main reason for the accumulation of oil on the left side of the vent. At this time, due to the influence of the oil accumulation area, the oil from the right chamber is difficult to move to the left chamber, and then flows out from the vent. By comparison, it is found that when the rotation speed is 6000–12,000 r/min, the air shear force is relatively small, and it is difficult to drag most of the lubricating oil in the accumulation area to the downstream. Therefore, in this speed range, as the speed increases, more lubricating oil flows into the accumulation area, and the scale of the oil accumulation area increases significantly, which aggravates the blockage effect on the right side of the vent, prompting more lubricating oil to flow out from the vent. Therefore, when the oil flow rate is 200 L/h and the speed is 6000–12,000 r/min, the amount of oil flowing out of the vent increases with the increase in the speed. However, when the rotational speed is increased to 15,000 r/min, the air shear force is increased.

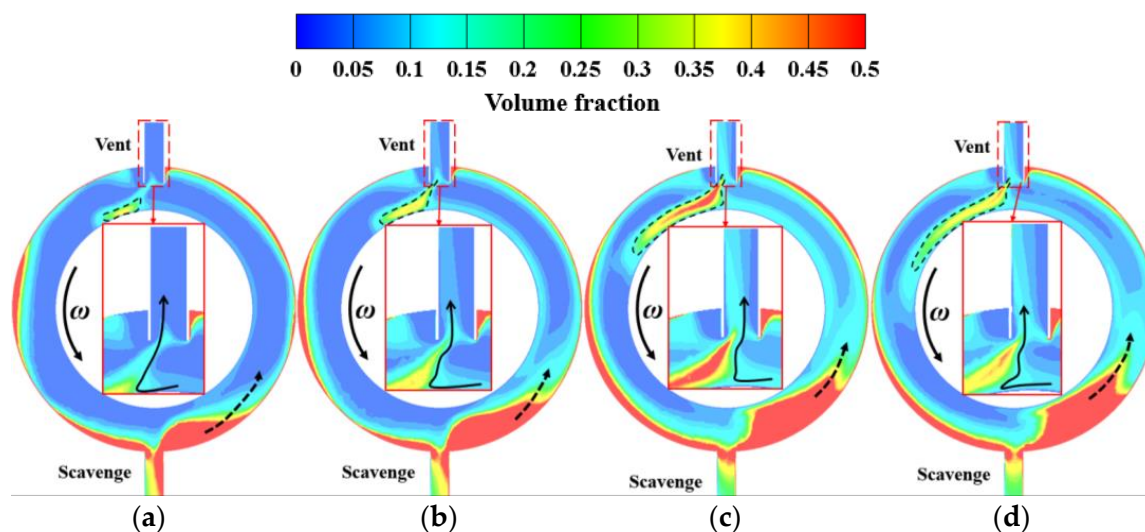


Figure 6. When the oil flow rate is 200 L/h, the oil volume fraction distribution in different revolutions is shown. (a) 6000 r/min; (b) 9000 r/min; (c) 12,000 r/min; (d) 15,000 r/min.

Figure 7 is the oil flow rate of 200 L/h, $h = 12$ mm embedded in the improved scheme of different speed cavity oil volume fraction distributions. From the diagram, it can be seen that compared to Figure 6, when the amount of lubricating oil increases to 1000 L/h, the

volume fraction of lubricating oil in the cavity increases significantly under each rotational speed condition. At the same time, with the increase in rotational speed, the volume fraction of lubricating oil in the cavity near the vent basically does not change much. Although the shear force of the air in the cavity on the oil increases significantly with the increase in the rotational speed, the gravity effect of the oil is greater than the shear force of the air in the cavity on the oil. This is the main reason why the amount of lubricating oil flowing from the vent of the embedded improvement scheme in Figure 7 does not change significantly with the rotational speed.

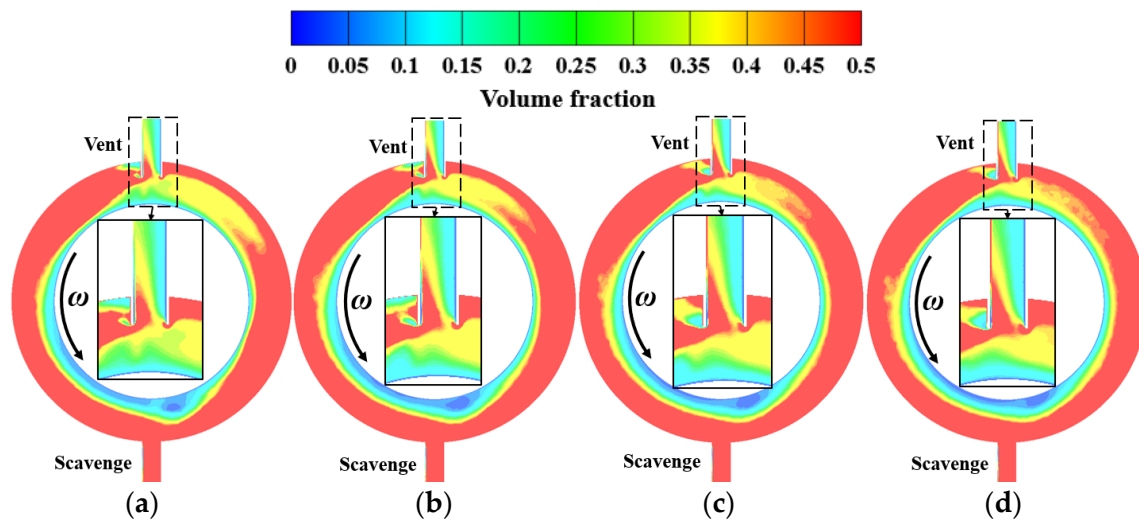


Figure 7. When the oil flow rate is 1000L / h, the oil volume fraction distribution in different revolutions is shown. (a) 6000 r/min; (b) 9000 r/min; (c) 12,000 r/min; (d) 15,000 r/min.

In order to explore the improvement mechanism of the embedded improvement scheme on the bearing chamber, the oil flow rate is 200 L/h, and the speed is 9000 r/min. The oil volume fraction distribution in the cavity of the embedded improvement scheme is shown in Figure 8. From the diagram, it can be seen that after the conventional bearing chamber is changed to the embedded improvement scheme, the embedded vent wall will block the lubricating oil in the cavity. At this time, the lubricating oil moves to the lower left of the vent. Under the action of air shear force, this part of the lubricating oil moves to the downstream scavenge port, which further increases the amount of lubricating oil at the scavenge port. In addition, the range of the lubricating oil accumulation area on the right side of the scavenge port is further increased. At this time, the lubricating oil in the accumulation area is relatively affected by gravity. The effect of air shear force is relatively small, and the lubricating oil in the accumulation area is swirling. With the increase in the embedding depth of the embedded improvement scheme, the embedded vent wall can further block the lubricating oil in the cavity, further inhibit the flow of lubricating oil from the vent, and more lubricating oil moves to the downstream scavenge.

The flow rate is 200 L/h, and the speed is 15,000 r/min. The volume fraction distribution of lubricating oil in the cavity is shown in Figure 9. From the diagram, it can be seen that when the rotational speed is increased from 9000 r/min to 15,000 r/min, the air in each bearing chamber carries a large amount of lubricating oil from the vent, the amount of lubricating oil flowing out from the vent increases and the scale of the lubricating oil accumulation zone on the right side of the scavenge decreases. At this time, the effect of gravity on the oil in the accumulation area is relatively small, and the effect of air shear force in the cavity is relatively large; the accumulation of oil on the right side of the scavenge port is obviously inhibited.

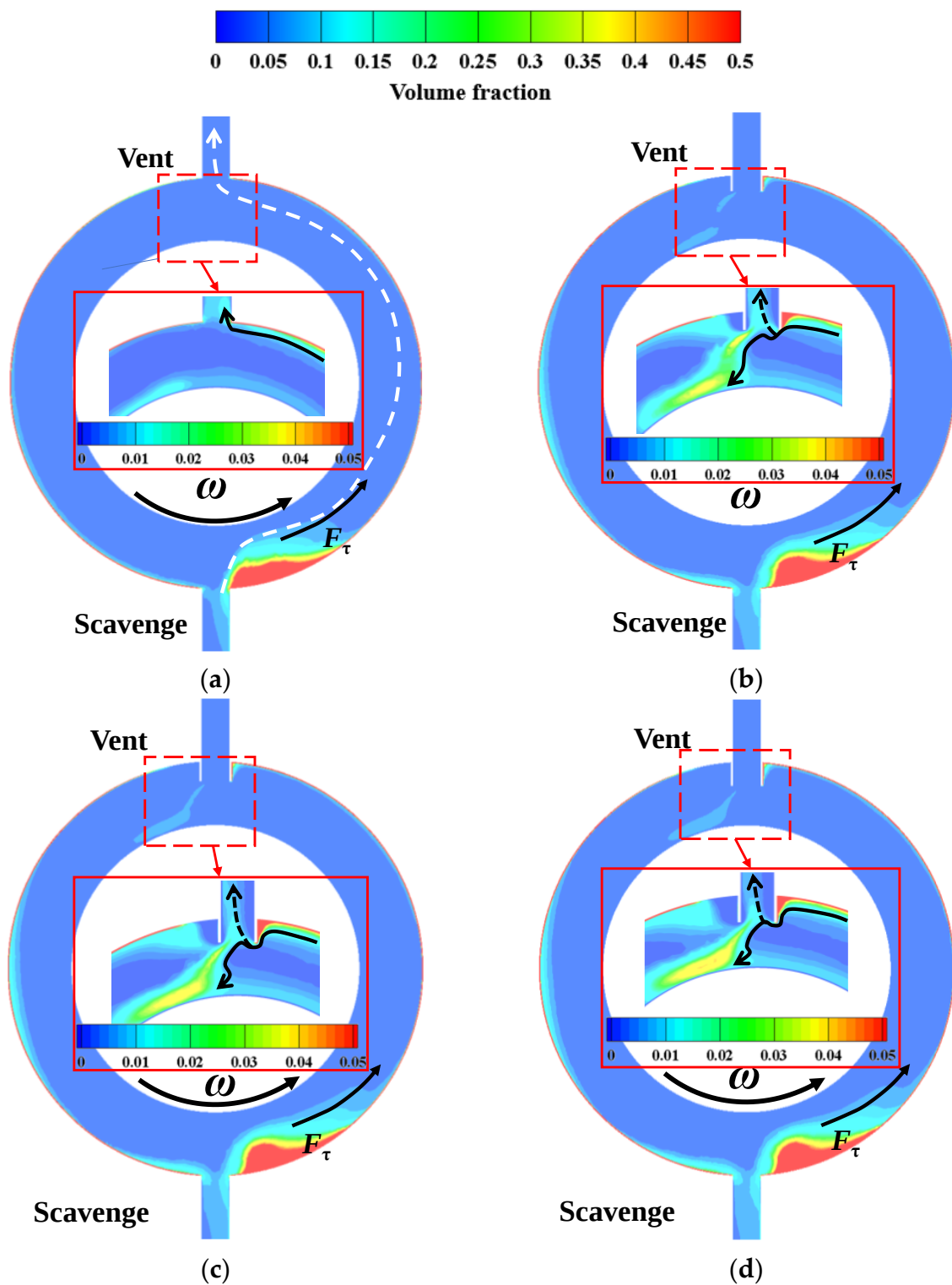


Figure 8. The volume fraction distribution of lubricating oil in the cavity is 200 L/h and the speed is 9000 r/min. (a) Norma; (b) $h = 8$ mm; (c) $h = 10$ mm; (d) $h = 12$ mm.

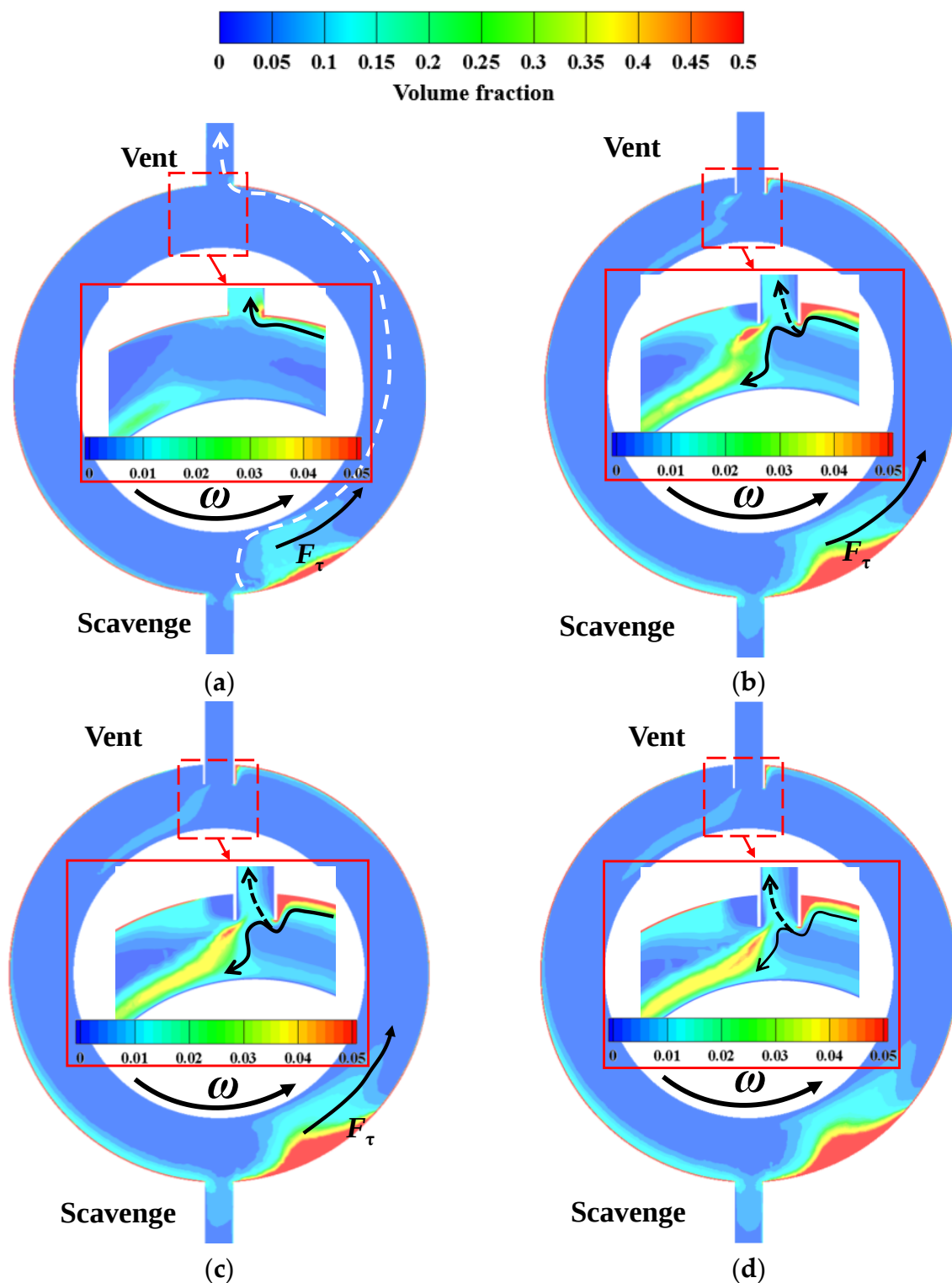


Figure 9. The volume fraction distribution of lubricating oil in the cavity is 200 L/h and the speed is 15,000 r/min. (a) Norma; (b) $h = 8$ mm; (c) $h = 10$ mm; (d) $h = 12$ mm.

The comparison of the oil volume fraction in the cavity embedded in the improved scheme is shown in Figure 10. It can be seen from the figure that when the speed is the same, the volume fraction of lubricating oil in each bearing chamber increases with the increase in the amount of lubricating oil. When the oil flow is the same, the volume fraction of the oil in each bearing cavity decreases with the increase in the rotational speed. This is

due to the increase in the amount of lubricating oil flowing from the scavenge and the vent after the speed increases.

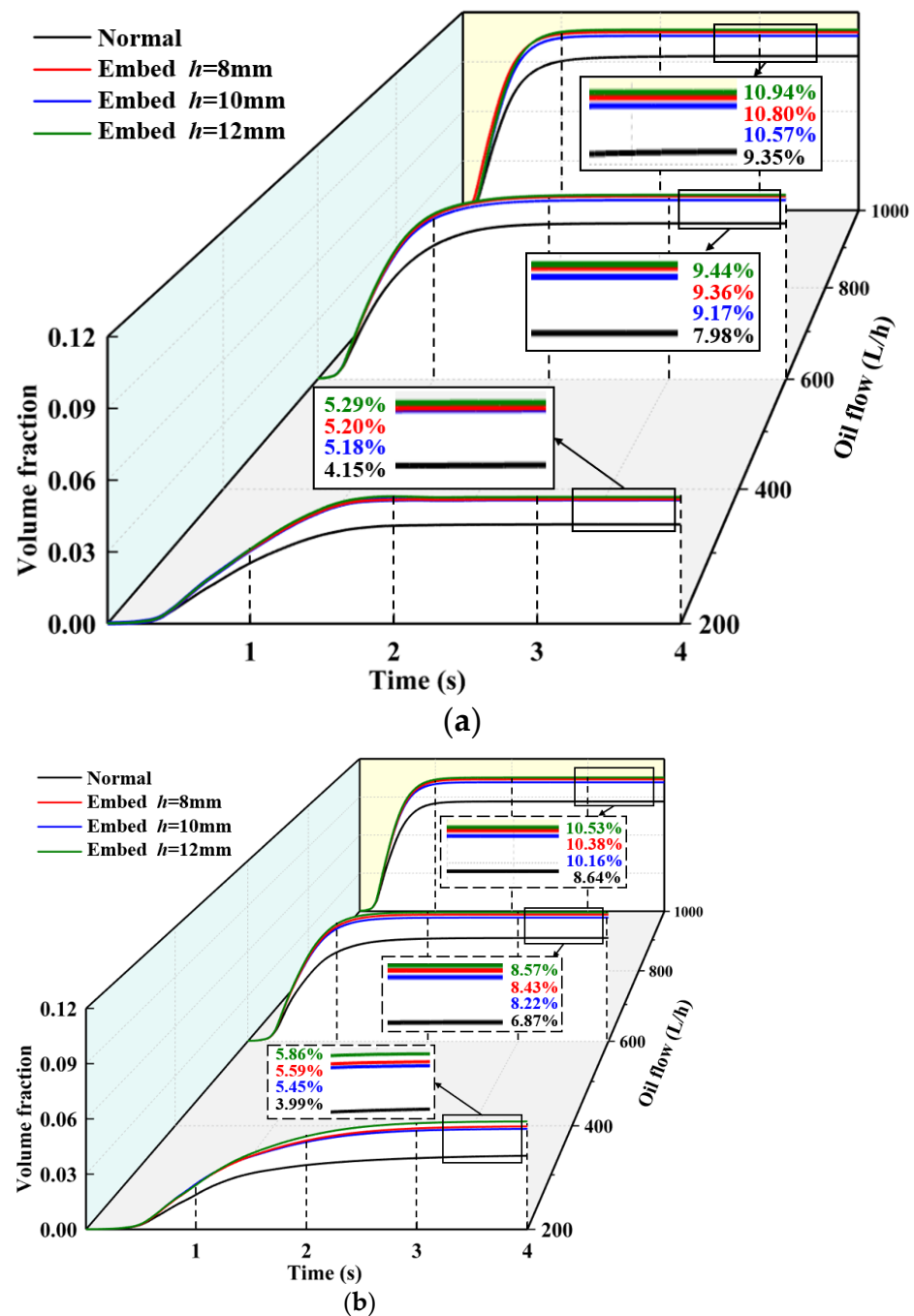


Figure 10. Comparison diagram of the oil volume fraction in the cavity. (a) 9000 r/min; (b) 15,000 r/min.

It is defined that when the volume fraction of lubricating oil in the cavity reaches 95% of the stable value, it can be identified as the stable stage. Through comparison, it is found that when the number of revolutions and the amount of lubricating oil are the same, compared with the conventional bearing chamber, the time of the embedded improvement scheme to reach the stable stage is significantly reduced. At the same time, in the stable stage, the volume fraction of lubricating oil in the cavity of the embedded improvement scheme is significantly higher than that of the conventional bearing chamber. With the increase in the embedded depth of the embedded improvement scheme, the outflow of lubricating oil from the vent is further inhibited, and the volume fraction of lubricating oil

in the cavity of the embedded improvement scheme is further increased. Figure 5 shows that compared to the conventional bearing chamber, when the speed is 9000 r/min, the oil flow rate is 200 L/h and 1000 L/h, respectively, the oil flow from the vent of the embedded improvement scheme $h = 12$ mm is reduced by 6.67 g/s and 28.27 g/s, respectively, and the oil flow from the scavenge is increased by 6.61 g/s and 27.73 g/s, respectively. When the speed is 15,000 r/min and the oil flow is 200 L/h and 1000 L/h, respectively, the amount of oil flowing out of the vent is reduced by 10.09 g/s and 32.55 g/s, respectively, and the amount of oil flowing out of the scavenge is increased by 10.22 g/s and 32.57 g/s, respectively. The decrease in lubricating oil at the vent of the embedded improvement scheme is greater than the increase in lubricating oil at the scavenge, which is the main reason for the increase in the lubricating oil volume fraction in the cavity of the embedded improvement scheme.

3.1.3. Scavenge Efficiency Analysis

The scavenge efficiency of the embedded improvement scheme is shown in Figure 11. It can be seen from the figure that when the oil flow rate is 200 L/h, the scavenge efficiency of the embedded improvement scheme decreases first and then increases with the increase in the rotational speed. When the amount of lubricating oil is 600 L/h and 1000 L/h, the scavenge efficiency of the embedded improvement scheme does not change much with the speed. Figure 5 shows that when the amount of oil is 200 L/h and the speed is 6000–12,000 r/min, the amount of oil flowing out of the vent increases with the increase in the speed, and the amount of oil flowing out of the scavenge decreases with the increase in the speed. When the rotational speed is increased to 15,000 r/min, the amount of oil flowing out from the vent is significantly reduced, and the amount of oil flowing out from the scavenge is significantly increased. This is the main reason why the scavenge efficiency of the embedded improvement scheme decreases first and then increases with the increase in the rotational speed when the oil flow rate is 200 L/h. Through comparison, it is found that when the oil flow rate and rotational speed are the same, the scavenge efficiency of the embedded improvement scheme is significantly higher than that of the conventional bearing cavity. This is because compared with the conventional bearing chamber, the embedded improvement scheme can suppress the flow of lubricating oil from the vent. At this time, the amount of lubricating oil flowing from the scavenge increases and the amount of lubricating oil flowing from the vent decreases. In addition, with the increase in embedding depth, the scavenge efficiency of the embedded improvement scheme is further increased. Among them, when the oil flow rate is 200 L/h and the speed is 15,000 r/min, the scavenge efficiency of the embedded improvement scheme is the most obvious. At this time, compared to the conventional bearing chamber, with the increase in the embedding depth, the scavenge efficiencies of the three slope improvement schemes are increased by 16.72%, 18.80% and 20.19%, respectively.

3.2. Analysis of Calculation Results of Slope Improvement Scheme

In this section, three kinds of scavenge port depths are proposed for the slope improvement scheme, namely $l = 40$ mm, $l = 48$ mm and $l = 56$ mm. The numerical simulation of the oil–gas two-phase flow field structure of different slope improvement schemes is carried out, and then the mechanism of the slope improvement scheme on the oil–gas two-phase flow field structure inside the bearing cavity is obtained, which provides a reference for the improvement of the conventional bearing chamber.

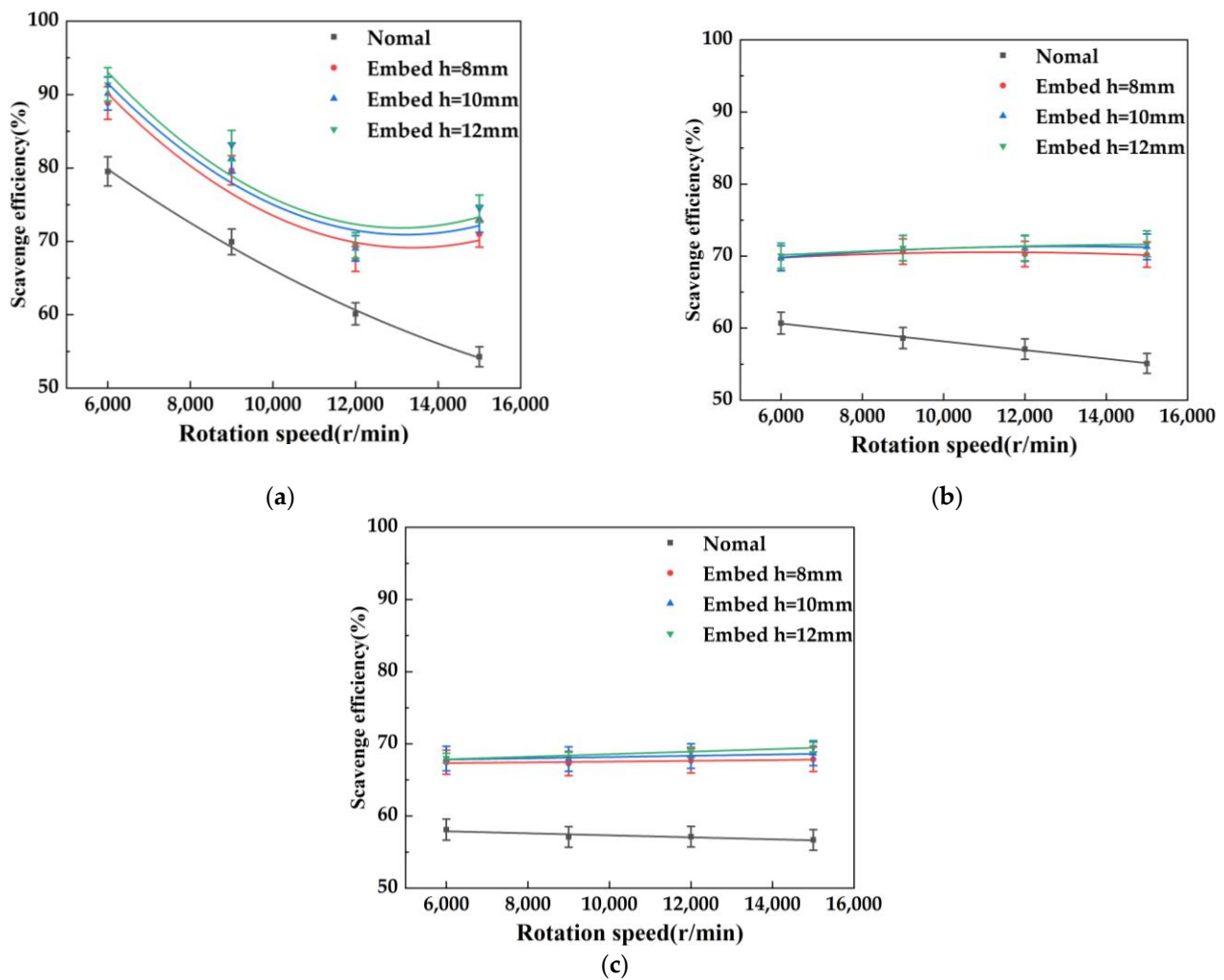


Figure 11. Comparison chart of scavenge efficiency. (a) 200 L/h; (b) 600 L/h; (c) 1000 L/h.

3.2.1. Leakage Analysis

The oil leakage of the slope improvement scheme is shown in Figure 12. Through comparison, it is found that when the oil flow rate and rotational speed are the same, compared with the conventional bearing chamber, the amount of oil flowing out from the vent of the slope improvement scheme decreases and the amount of oil flowing out from the scavenge port increases. It can be seen that the slope improvement scheme is more conducive to the outflow of lubricating oil from the scavenge port. At the same time, with the increase in the depth of the oil return groove, the amount of oil flowing from the vent is further reduced and the amount of oil flowing from the scavenge port is further increased. This is because after the depth of the oil return groove increases, the drag effect of the air in the cavity on the oil near the scavenge port is further suppressed.

3.2.2. Analysis of Volume Fraction of Lubricating Oil in Cavity

The oil flow rate is 200 L/h, and the speed is 9000 r/min. The oil volume fraction distribution in the chamber of the slope improvement scheme is shown in Figure 13, where the right side of the white interface is the trajectory of the oil in the accumulation area. Through comparison, it is found that after changing the conventional bearing cavity to the slope improvement scheme, it is beneficial for the oil to flow into the scavenge port, and the range of the oil accumulation area on the right side of the oil return port is obviously reduced. At the same time, with the increase in the groove depth of the oil return groove in the slope improvement scheme, the drag effect of the air in the cavity on the oil near the

scavenge port is further suppressed, so the scale of the oil accumulation area on the right side of the scavenge port is obviously reduced.

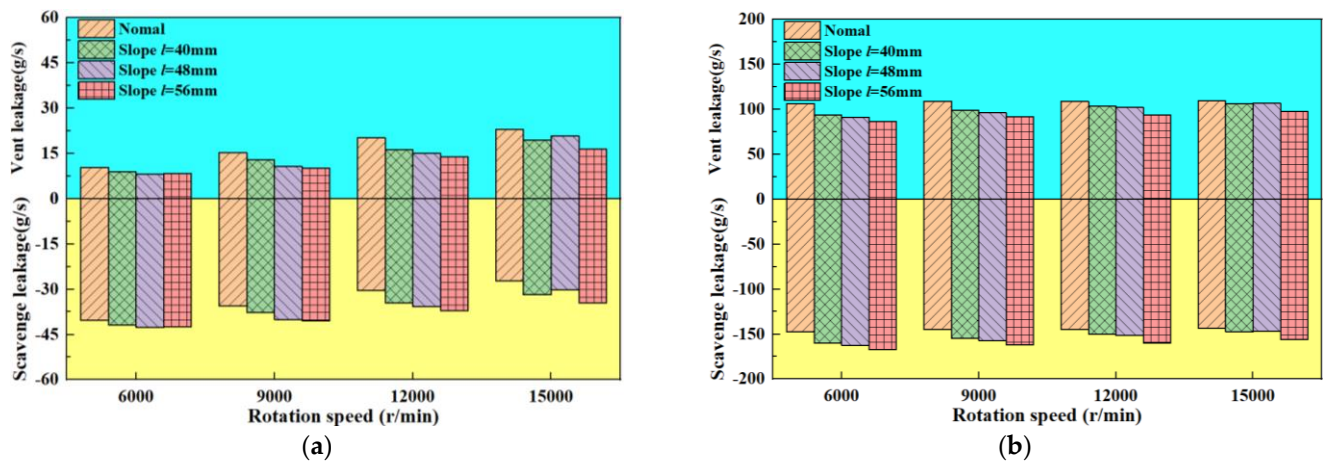


Figure 12. Comparison chart of oil leakage. (a) 200 L/h; (b) 1000 L/h.

The volume fraction distribution in the oil cavity with a flow rate of 200 L/h and a speed of 15,000 r/min is shown in Figure 14. From the diagram, it can be seen that after the rotational speed is increased from 9000 r/min to 15,000 r/min, the air carries a large amount of lubricating oil from the vent, the amount of lubricating oil flowing out from the vent increases, the amount of lubricating oil flowing out from the vent decreases, the scale of the lubricating oil accumulation area on the right side of the scavenge port decreases and the lubricating oil accumulation near the scavenge port of each slope improvement scheme basically disappears.

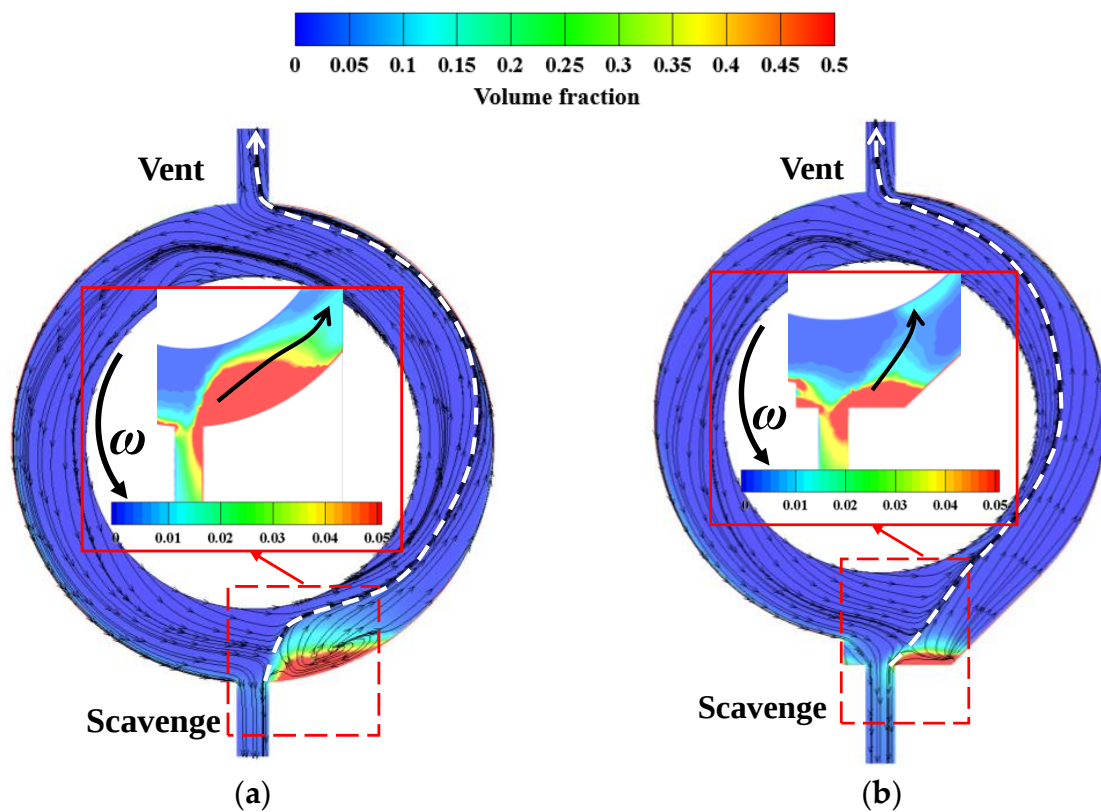


Figure 13. Cont.

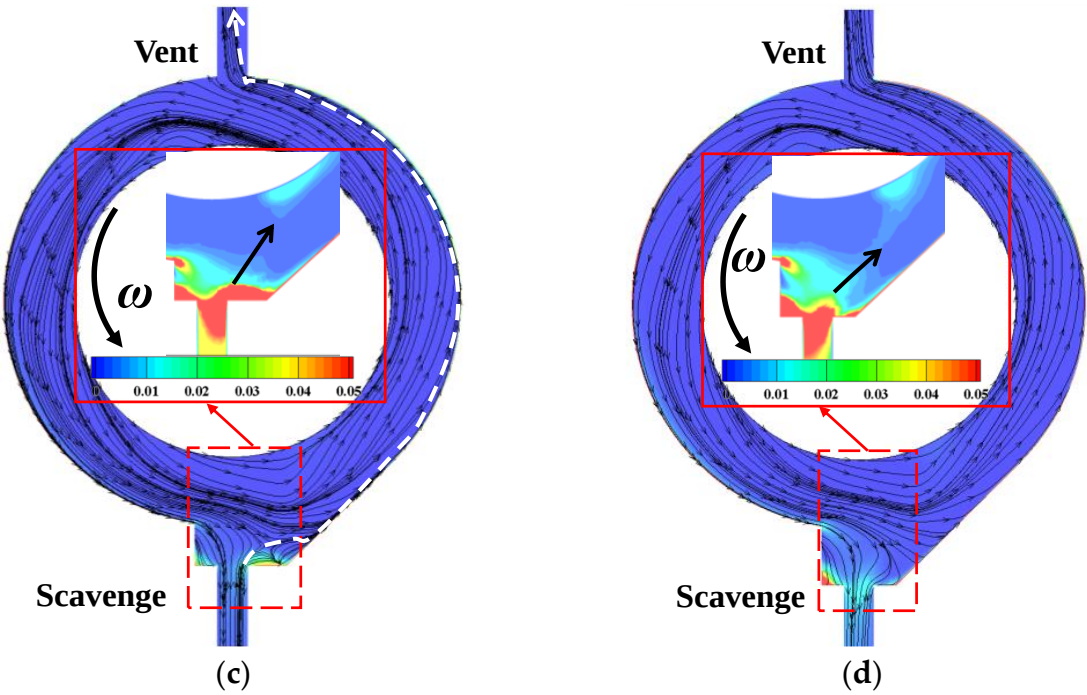


Figure 13. The volume fraction distribution of lubricating oil in the cavity is 200 L/h and the rotational speed is 9000 r/min. (a) Normal; (b) $l = 40$ mm; (c) $l = 48$ mm; (d) $l = 56$ mm.

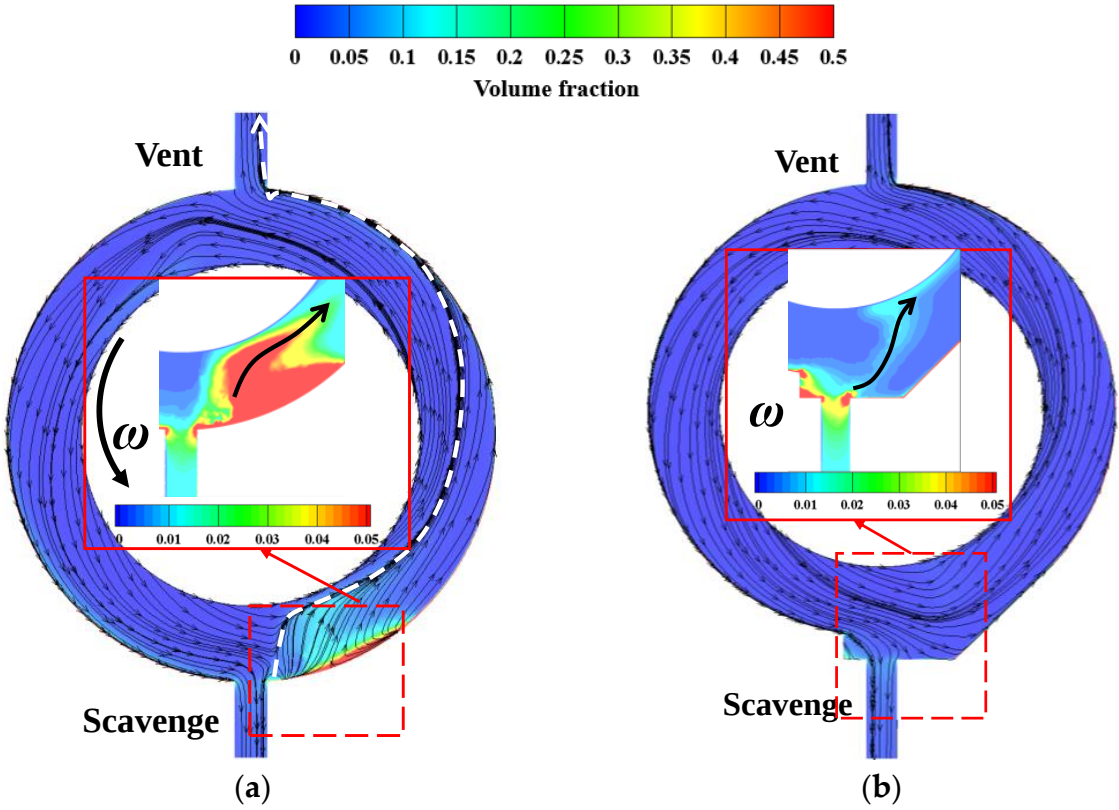


Figure 14. *Cont.*

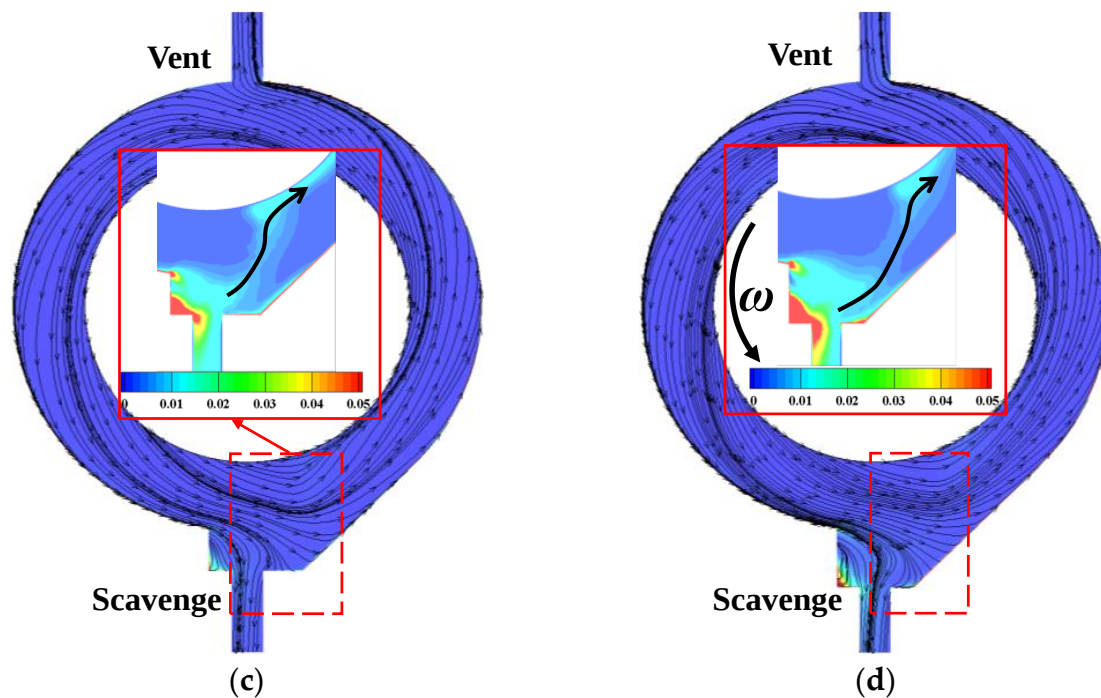


Figure 14. The volume fraction distribution of lubricating oil in the cavity is 200 L/h and the rotational speed is 15,000 r/min. (a) Normal; (b) $l = 40$ mm; (c) $l = 48$ mm; (d) $l = 56$ mm.

The comparison of the oil volume fraction in the slope improvement scheme is shown in Figure 15. Through comparison, it is found that when the number of revolutions and the amount of lubricating oil are the same, compared with the conventional bearing chamber, the time of the slope improvement scheme to reach the stable stage is significantly reduced. At the same time, in the stable stage, the volume fraction of lubricating oil in the cavity of the slope improvement scheme is significantly lower than that of the conventional bearing chamber. With the increase in the depth of the oil return tank in the slope improvement scheme, the amount of lubricating oil flowing out from the return oil further increases, and the volume fraction of lubricating oil in the cavity of the slope improvement scheme further decreases.

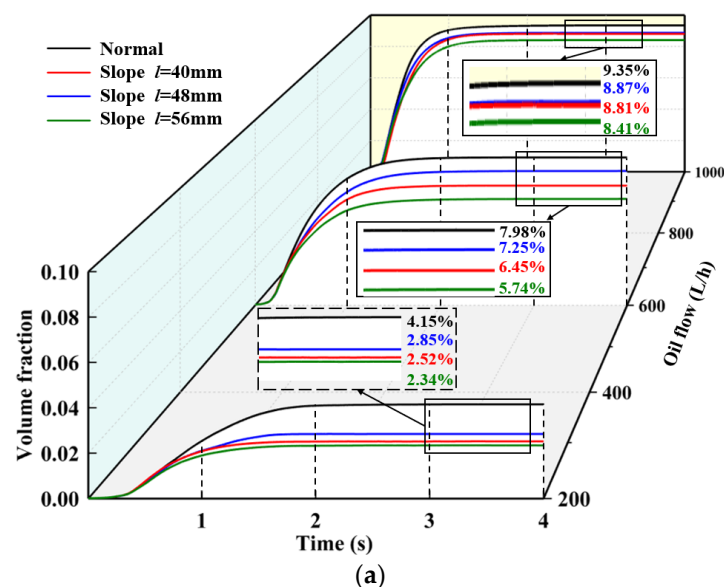


Figure 15. Cont.

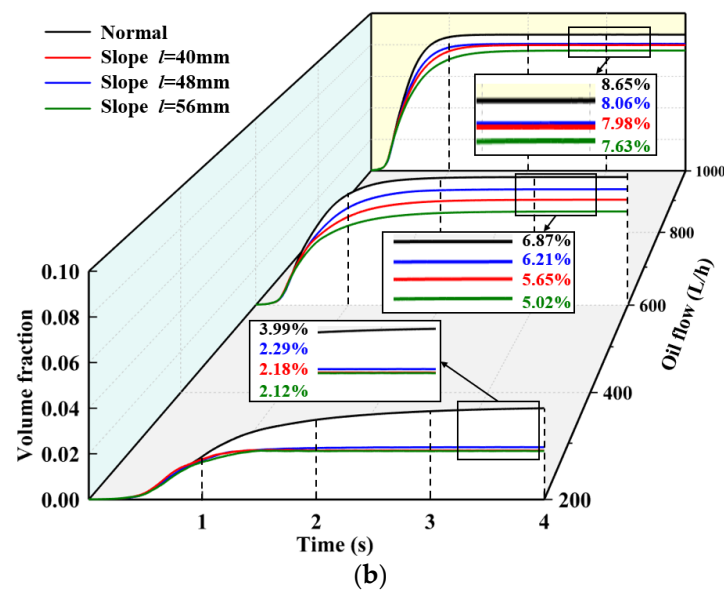


Figure 15. Comparison diagram of oil volume fraction in cavity. (a) 9000 r/min; (b) 15,000 r/min.

3.2.3. Scavenge Efficiency Analysis

The scavenge efficiency of the slope improvement scheme is shown in Figure 16. From the diagram, it can be seen that when the oil flow rate is the same, with the increase in the rotational speed, the scavenge efficiency of each bearing chamber scheme generally decreases. Through comparison, it is found that when the oil flow rate and rotational speed are the same, the scavenge efficiency of the slope improvement scheme is significantly higher than that of the conventional bearing chamber. At the same time, with the increase in the oil return tank, the oil return efficiency of the slope improvement scheme is further increased. Among them, when the oil flow rate is 200 L/h and the speed is 15,000 r/min, the scavenge efficiency of the embedded improvement scheme is the most obvious. At this time, compared with the conventional bearing chamber, as the depth of the oil return groove increases, the scavenge efficiency of the three slope improvement schemes increase by 4.88%, 7.84% and 13.43%, respectively.

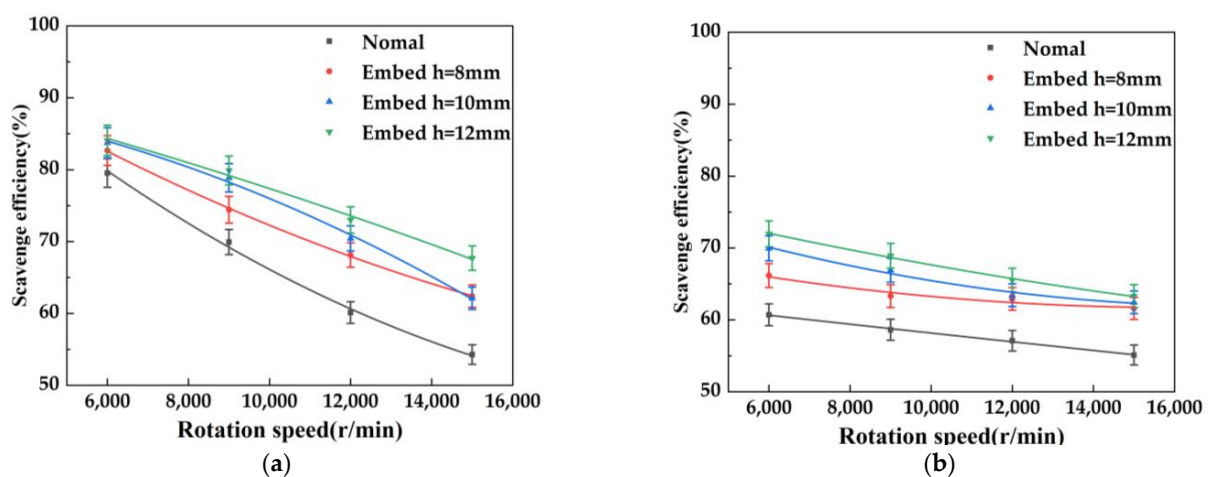


Figure 16. Cont.

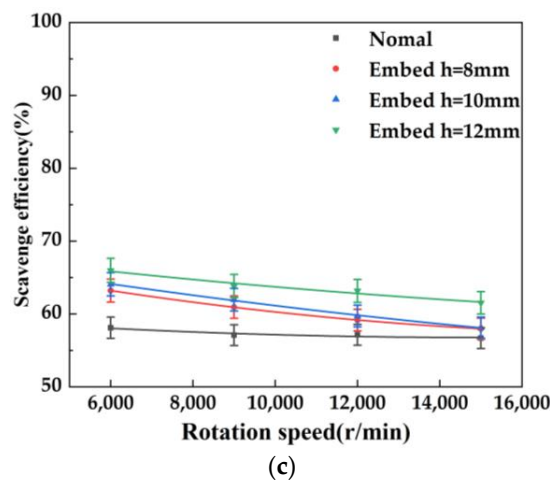


Figure 16. Comparison chart of scavenge efficiency. (a) 200 L/h; (b) 600 L/h; (c) 1000 L/h.

3.3. Analysis of Calculation Results of Combined Improvement Scheme

According to the aforementioned content, it can be seen that the embedded improvement scheme $h = 12$ mm and the slope improvement scheme $l = 56$ mm have higher scavenge efficiency and better improvement effects on the oil–gas two-phase flow field structure in the bearing chamber. Therefore, based on the embedded improvement scheme and the slope improvement scheme, this chapter proposes a combined improvement scheme and explores the mechanism of the combined improvement scheme on the oil–gas two-phase flow field structure in the bearing chamber. Among them, the embedded depth of the vent in the combined improvement scheme is $h = 12$ mm, and the depth of the scavenge port is $l = 56$ mm.

3.3.1. Leakage Analysis

Figure 17 shows the relationship between the amount of lubricating oil flowing from the vent and the scavenge port and the rotational speed. Through comparison, it is found that when the oil flow rate and rotational speed are the same, the amount of oil flowing out from the vent of the embedded improvement scheme is lower than that of the conventional bearing cavity, and the amount of oil flowing out from the scavenge port is higher than that of the conventional bearing chamber. The amount of lubricating oil flowing from the vent of the slope improvement scheme is lower than that of the conventional bearing cavity, and the amount of lubricating oil flowing from the scavenge port is higher than that of the conventional bearing chamber. Under various working conditions, the amount of lubricating oil flowing from the vent is lower than that of other bearing chambers, and the amount of lubricating oil flowing from the scavenge port is higher than that of other bearing chambers.

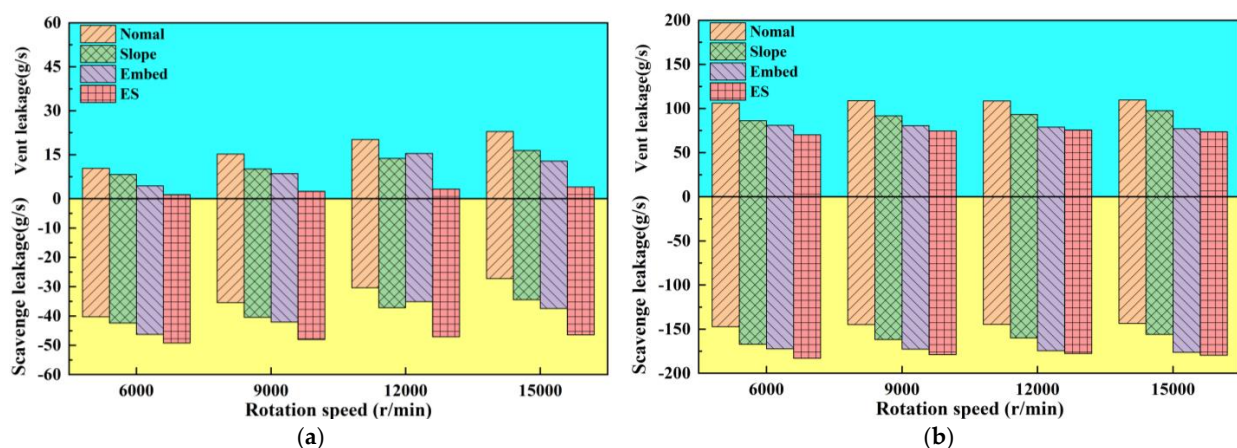


Figure 17. Comparison chart of oil leakage. (a) 200 L/h; (b) 1000 L/h.

3.3.2. Analysis of Volume Fraction of Lubricating Oil in Cavity

Two speeds of 9000 r/min and 15,000 r/min were selected for comparative analysis. The variation of the volume fraction of lubricating oil in the conventional bearing chamber and the three improved schemes with time is shown in Figure 18. From the diagram, it can be seen that when the number of revolutions and the amount of lubricating oil are the same, in the stable stage, compared with the conventional bearing chamber, the volume fraction of lubricating oil in the slope improvement scheme cavity is lower than that in other bearing chambers, and the volume fraction of lubricating oil in the embedded improvement scheme cavity is higher than that in other bearing chambers. Under the condition that the oil flow rate is 200 L/h, the volume fraction of the oil in the cavity is between the conventional bearing cavity and the embedded improvement scheme. When the oil flow rate is 600 L/h and 1000 L/h, the oil volume fraction in the cavity of the combined improvement scheme is higher than that of the embedded improvement scheme and the slope improvement scheme, and lower than that of the conventional bearing chamber.

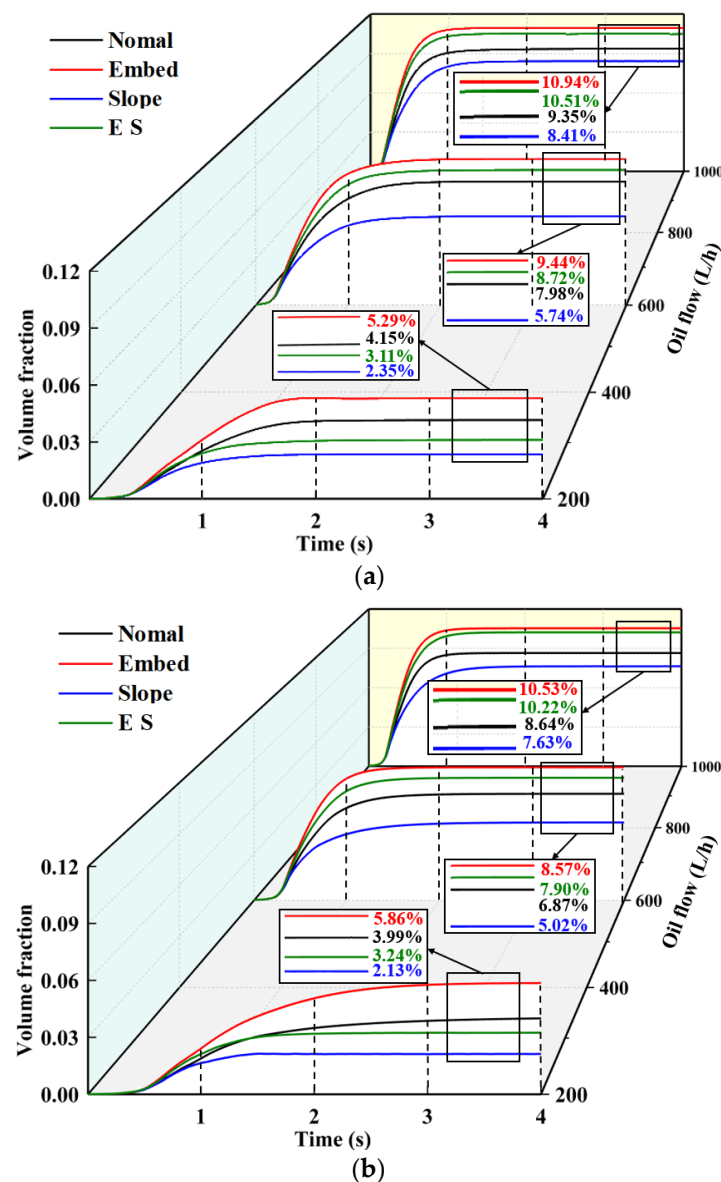


Figure 18. Comparison diagram of oil volume fraction in cavity. (a) 9000 r/min; (b) 15,000 r/min.

Figure 19 shows the oil flow rate of 200 L/h, the speed of 9000 r/min, and the distribution of the oil volume fraction in the cavity. It can be seen from the diagram that

the oil accumulation area on the right side of the scavenge port is clearly visible. Through comparison, it is found that the combined improvement scheme can take into account the advantages of the embedded improvement scheme and the slope improvement scheme. Not only can the embedded vent wall block the lubricating oil in the cavity, but it can also facilitate the lubricating oil in the accumulation area on the right side of the scavenge port to flow into the scavenge port. The volume fraction of lubricating oil in the cavity of the combined improvement scheme is lower than that of the conventional bearing chamber.

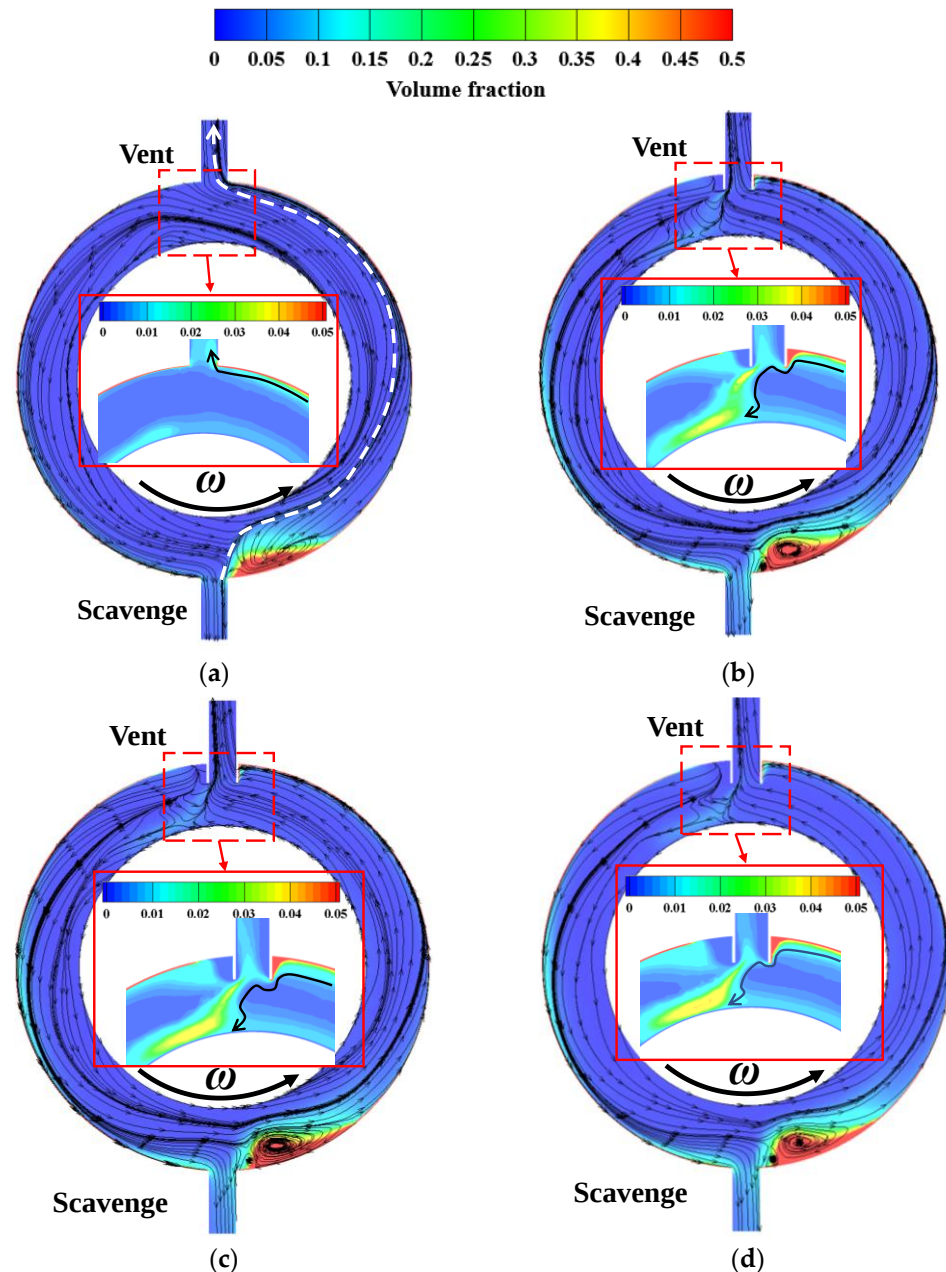


Figure 19. The volume fraction distribution of lubricating oil in the cavity is 200 L/h and the speed is 9000 r/min. (a) Normal; (b) Embed; (c) Slope; (d) ES.

Figure 20 shows the distribution of the oil volume fraction in the cavity when the oil flow rate is 200 L/h and the rotation speed is 15,000 r/min. From the diagram, it can be seen that compared with the speed of 9000 r/min, when the speed is increased to 15,000 r/min, the drag effect of the air in the cavity on the lubricating oil is further enhanced, and the drag trend is clearly visible. The air carries a large amount of lubricating oil from the vent, and the oil accumulation area on the right side of the scavenge port of the conventional

bearing chamber is reduced to a certain extent, and the volume fraction of lubricating oil in the cavity is reduced. The scale of the oil accumulation area on the left side of the vent of the combined improvement scheme increases, the oil in the oil return tank decreases to a certain extent and the volume fraction of the oil in the cavity decreases.

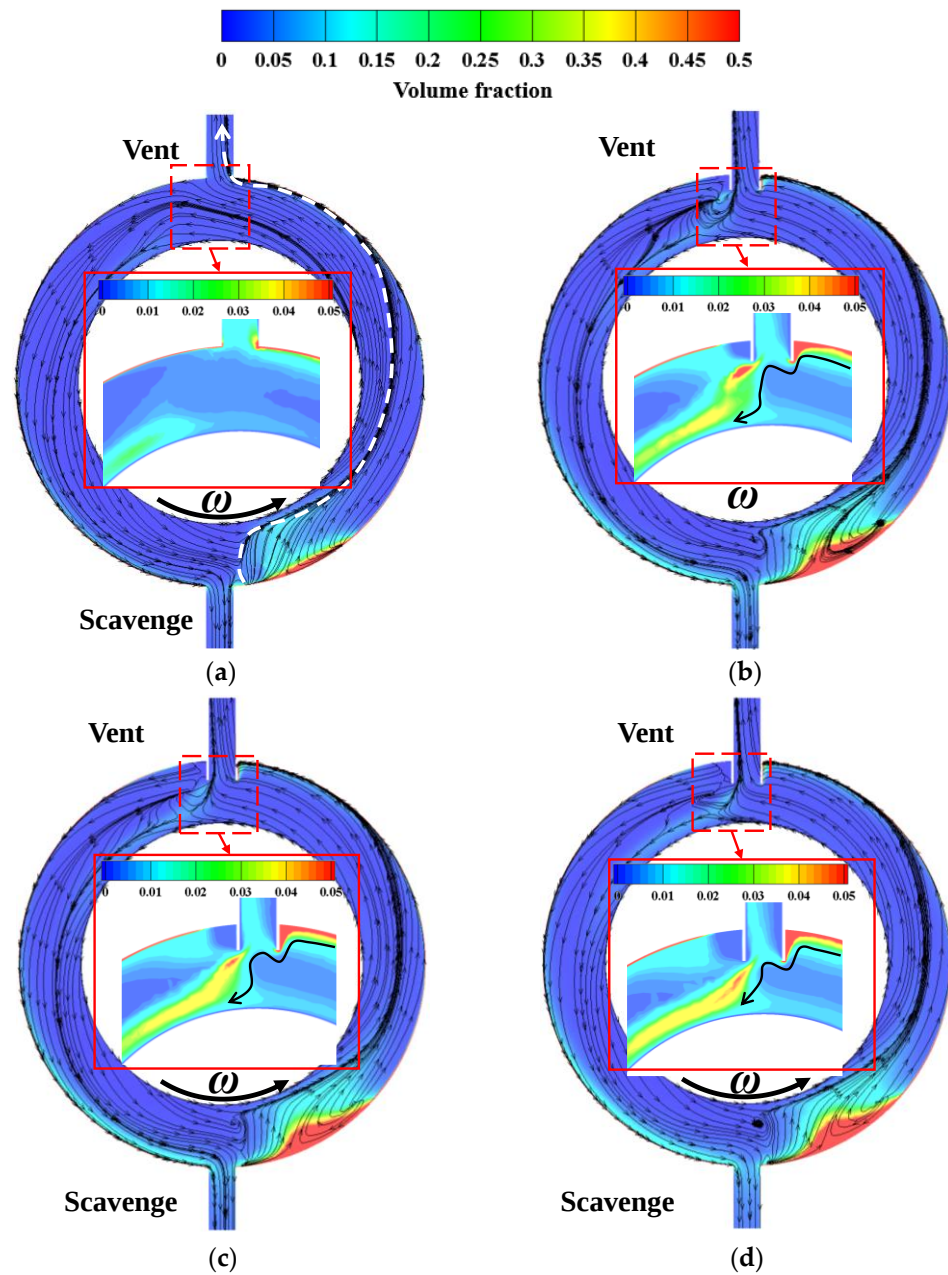


Figure 20. The lubricating oil is 200 L/h, and the rotational speed is 15,000 r/min. The distribution map of the volume fraction of lubricating oil in the cavity is drawn. (a) Normal; (b) Embed; (c) Slope; (d) ES.

Figure 21 shows the oil flow rate of 1000 L/h, the speed of 9000 r/min and the distribution of the oil volume fraction in the cavity. It can be seen from the figure that compared to Figure 19, when the speed is constant, after the amount of oil increases, the volume fraction of oil in the three bearing chamber improvement schemes increases, and the oil near the scavenge port and the vent increases. Through comprehensive comparison, it is found that under the condition of a flow rate of 1000 L/h, compared with the conventional bearing cavity, the amount of lubricating oil blocked by the right wall of the vent of the embedded and combined improvement scheme is relatively large, and the volume fraction of lubricating oil in the cavity is further increased. In the slope improvement scheme, the

oil volume on the right side of the scavenge port and the vent is relatively small, and the oil volume fraction in the cavity is smaller than that in the conventional bearing chamber.

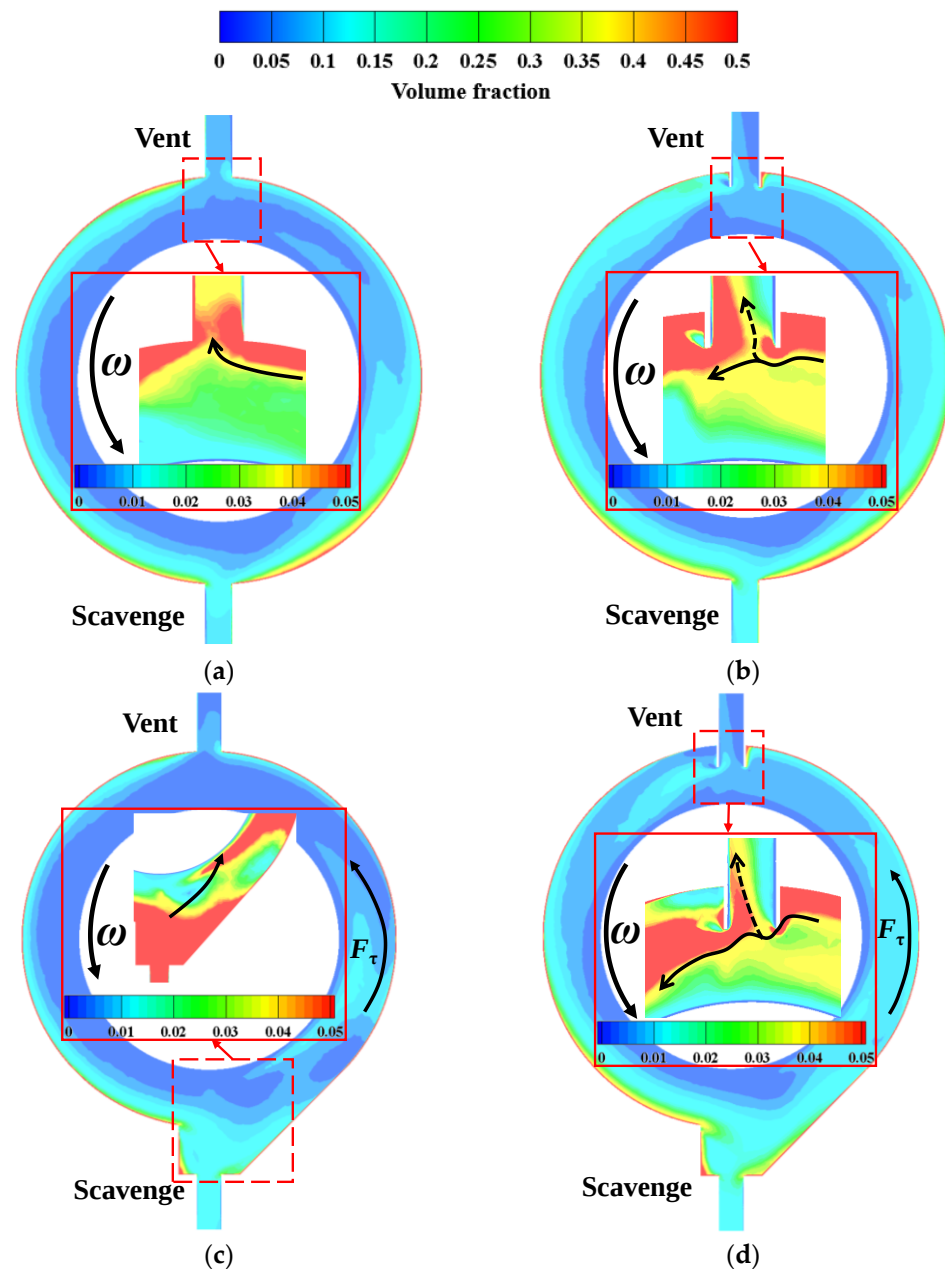


Figure 21. The volume fraction distribution of lubricating oil in the cavity is 1000 L/h and the speed is 9000 r/min. (a) Normal; (b) Embed; (c) Slope; (d) ES.

Figure 22 shows the distribution of the oil volume fraction in the cavity when the oil flow rate is 1000 L/h and the rotation speed is 15,000 r/min. Through comparison, it is found that under the condition of an oil flow rate of 1000 L/h and speed of 15,000 r/min, the volume fraction of oil in the cavity is higher than that in the conventional bearing chamber. The slope improvement scheme has a better effect on the wall of the bearing cavity, and the volume fraction of the lubricating oil in the cavity is lower than that of the conventional bearing chamber.

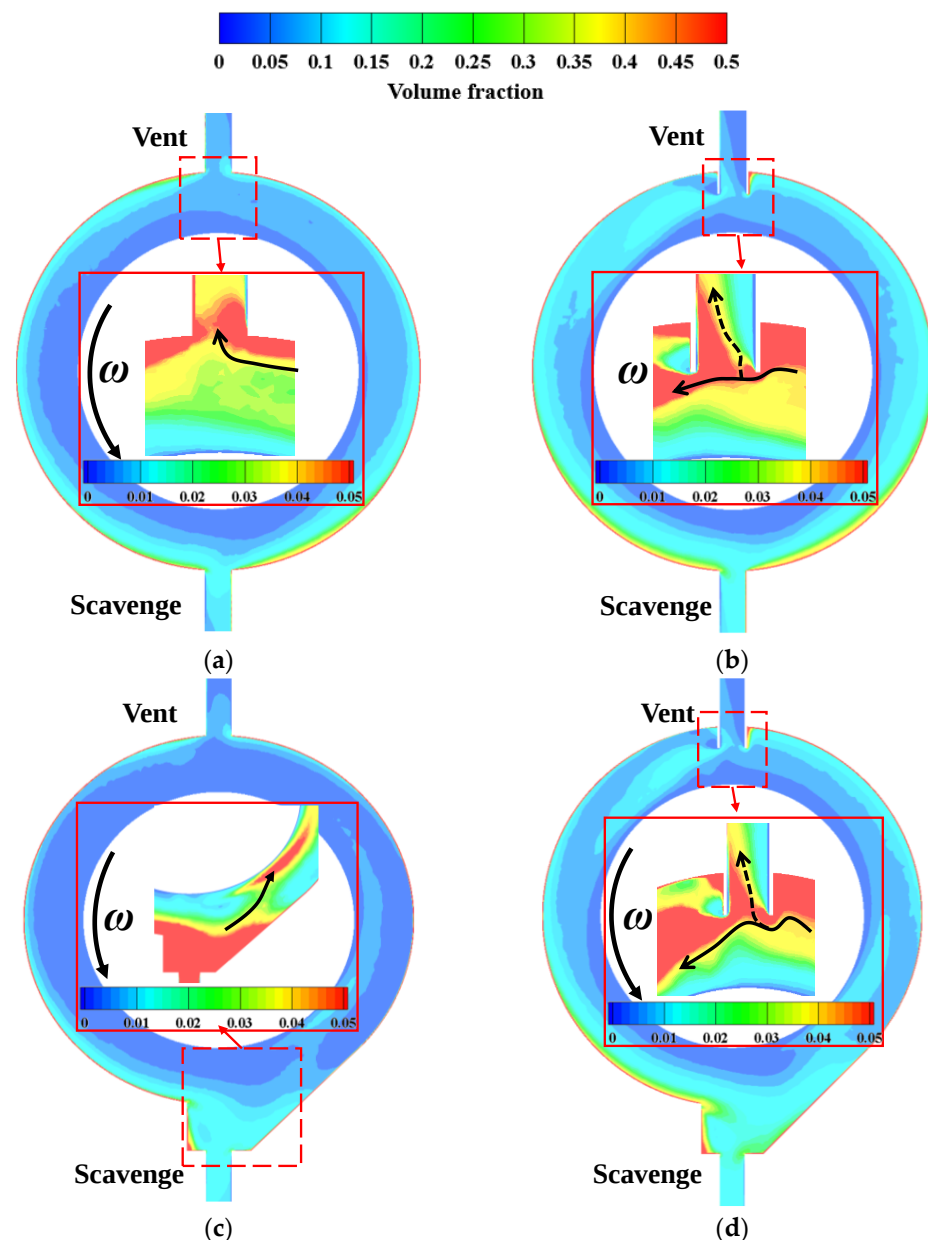


Figure 22. The volume fraction distribution of lubricating oil in the cavity is 1000 L/h and the speed is 15,000 r/min. (a) Normal; (b) Embed; (c) Slope; (d) ES.

3.3.3. Scavenge Efficiency Analysis

Figure 23 is the comparison of scavenge efficiency of different improvement schemes. By comparison, it is found that the scavenge efficiencies of the three improved schemes are significantly higher than that of the conventional bearing chamber under the condition of constant oil flow and rotational speed. The combined improvement scheme will take into account the advantages of the embedded improvement and the slope improvement scheme. The amount of oil flowing out from the vent is lower than that of other bearing chambers, and the amount of oil flowing out from the scavenge port is higher than that of other bearing chambers. The scavenge efficiency is significantly higher than the embedded and slope improvement scheme, and the oil return effect of the bearing cavity is better. Compared with the conventional bearing chamber structure, when the oil flow rate is 200 L/h and the speed is 15,000 r/min, the scavenge efficiencies of the three improved schemes are the most obvious, and the scavenge efficiencies of the embedded, slope and combined improvement schemes are increased by 20.19%, 13.43% and 37.94%, respectively.

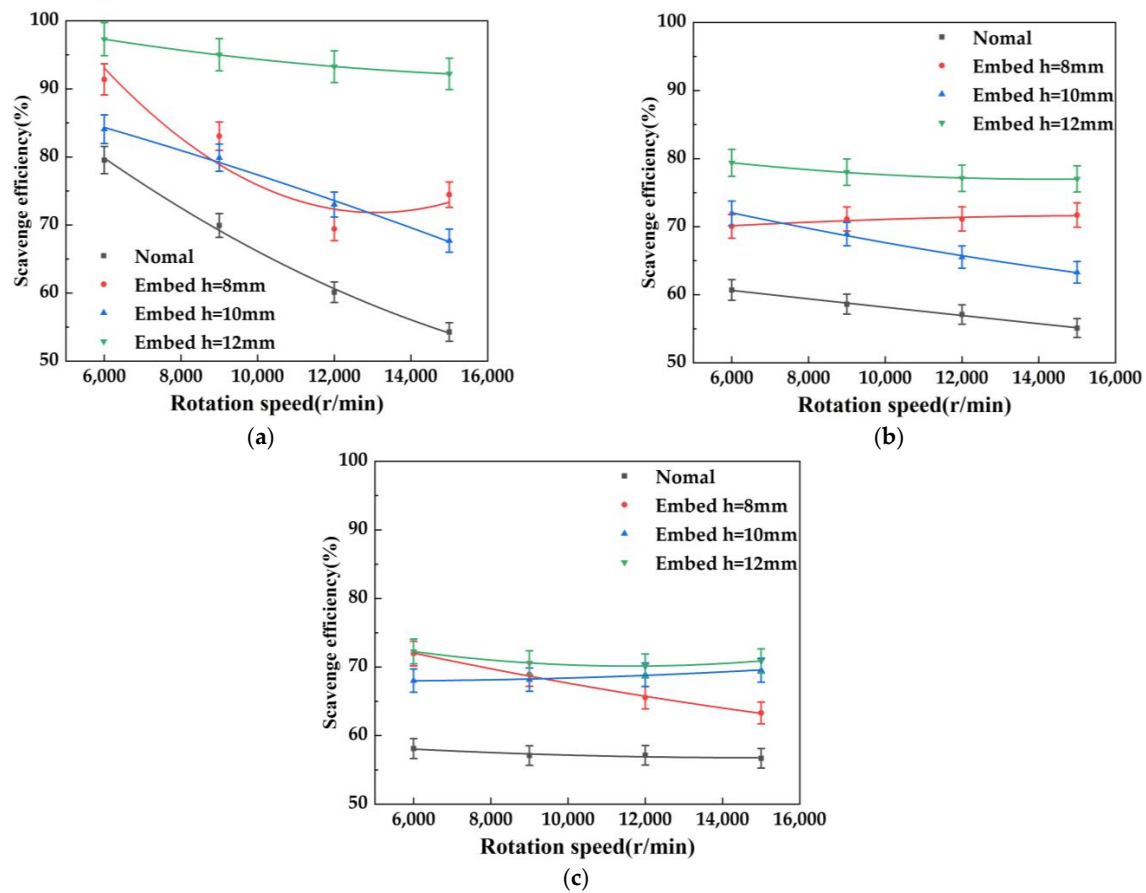


Figure 23. Comparison diagram of scavenge efficiency. (a) 200 L/h; (b) 600 L/h; (c) 1000 L/h.

3.4. Analysis of Flow Improvement Mechanism

The flow control mechanism model of the combined improvement scheme is shown in Figure 24. The wall of the vent embedded in the improved scheme blocks the lubricating oil in the cavity, so that a part of the lubricating oil flows out from the scavenge port. The right side of the scavenge port of the slope improvement scheme is an inclined slope, which is beneficial for the oil to flow into the scavenge port. The combined improvement scheme will take into account the advantages of the embedded improvement and the slope improvement scheme, effectively inhibit the outflow of lubricating oil from the vent and then make more lubricating oil flow out from the scavenge port, and the scavenge efficiency is greatly improved.

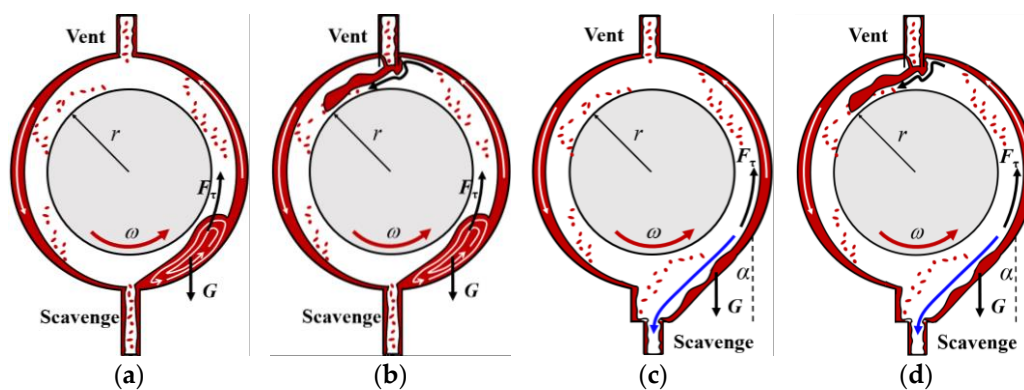


Figure 24. Flow control mechanism model of improved schemes. (a) Normal; (b) Embed; (c) Slope; (d) ES.

4. Conclusions

In this paper, the conventional bearing chamber structure is improved, and the influence of the improved scheme on the oil return characteristics and flow field structure of the bearing chamber is studied by unsteady numerical simulation. The following conclusions are obtained:

- (1) Compared with the conventional bearing chamber, the vent wall embedded in the improved scheme can effectively block the lubricating oil in the cavity. At the same time, with the increase in embedding depth, the amount of lubricating oil flowing out from the vent is further reduced, the amount of lubricating oil flowing out from the return port is further increased, the volume fraction of lubricating oil in the cavity is further increased and the scavenge efficiency is further improved.
- (2) The slope improvement scheme is beneficial to the oil on the right side of scavenge port to flow into the scavenge port, and the oil accumulation area on the right side of the scavenge port is obviously suppressed. At the same time, with the increase in the depth of the oil return groove, the drag effect of the air shear force in the cavity on the oil near the scavenge port is further weakened, the volume fraction of the oil in the cavity is further reduced and the scavenge efficiency is further improved.
- (3) The combined improvement scheme will take into account the advantages of the embedded improvement and the slope improvement scheme, effectively inhibit the outflow of lubricating oil from the vent and then make more lubricating oil flow out of the oil return port, and the scavenge efficiency is greatly improved. Compared with the conventional bearing chamber structure, when the oil flow rate is 200L / h and the speed is 15000r / min, the scavenge efficiencies of the three improved schemes are the most obvious, and the scavenge efficiencies of the embedded, slope and combined improvement schemes are increased by 20.19%, 13.43% and 37.94%, respectively.

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