

Structural Design and Performance Study of a Two-Stage Dynamic Pressure Oil-Air Separator

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Abstract

In an aircraft engine, high-speed rotating components generate significant heat during operation and therefore rely on lubricating oil for cooling and lubrication. In an open-loop engine, the lubricating oil is prone to mixing with gas during circulation, forming an oil-gas mixture that degrades its lubrication and cooling performance. Consequently, reducing the gas content in the supplied lubricating oil is of critical importance, and an oil-gas separation device is typically installed in the return line. Currently, dynamic-type oil-gas separators used in small engines suffer from insufficient separation efficiency, making it difficult to effectively separate oil from air. This paper investigates a two-stage dynamic oil-gas separator. First, the performance differences between single-stage and two-stage separation configurations are compared and analyzed. The results indicate that the two-stage oil-gas separator outperforms the single-stage oil-gas separator in terms of separation efficiency and oil consumption ratio. Second, the influence of the wake separator structure on the overall separation efficiency is examined, and it is determined that a wake separator with an orifice diameter of 1.5 mm achieves the best separation performance. The effect of the inlet area on the two-stage separator's performance is also explored, with results showing that an inlet area 1.75 times that of the initial model yields the best performance. Finally, a multi-operating-condition analysis is conducted on the optimized two-stage oil-gas separator. The results demonstrate that the optimized structure exhibits improved performance over the initial design in terms of separation efficiency, oil consumption ratio, and pressure drop.

Keywords: Oil-air separator; Two-stage oil-air separation; Separation efficiency; Pressure drop.

1. Introduction

The high-speed rotating bearings in aero-engines generate significant heat during operation. To ensure proper functioning and avoid direct contact between rolling elements and raceways, lubricating oil is injected under pressure through nozzles to cool and lubricate the bearings. Due to leakage from labyrinth seals, the lubricating oil mixes with air in the bearing chamber, forming an oil-air mixture. The fluid medium returned by the scavenge pump is thus an oil-air mixture. The entrained air is difficult to separate naturally. If the oil-air mixture enters the supply pump directly, it reduces the effective oil supply and significantly impairs the lubrication and cooling performance for the bearings and accessory gears, which in severe cases may lead to in-flight engine shutdown. Therefore, an oil-air separator installed between the scavenge pump and the oil tank is essential, ensuring the operational safety of the bearings and gears.

Michael Frank et al. 0used numerical simulation methods to verify the mechanisms underlying the effects of different geometric structures, gas-liquid flow rates, and other conditions. Citation: Ni, W.W. et al. [2] investigated the separation performance of key structures such as MAD under various flight conditions, including cold start and cruise. Their work contributed to the optimization of certain structural components and the enhancement of separation efficiency. David L. Sims et al. [3] developed a cylindrical oil-gas separator featuring a series of orifices in the inlet section. Leveraging the differential pressure, a fraction of the air is vented through these orifices, resulting in enhanced separation efficiency. Hutchison Richard M. et al. [4] devised a gear pump-based oil-gas separator. In this design, the separated oil is routed back to the tank via an outlet upstream of the gear meshing region, and the air is expelled at the same time. Junsuke Yabumoto et al. [5] designed a rotary bubble

separation device, in which a swirl chamber at the top performs preliminary oil-gas separation, and a centrally located perforated duct is used for air discharge. Yasuhiro Saito et al. [6] arranged baffles at both the upper and lower portions of the oil-gas separator, thereby preventing the ingress of lubricating oil into the exhaust line. Rollins Michael J. and Bell Melissa et al. [7] arranged a flat plate at the middle of the central tube, with the purpose of slowing the descending velocity of the returning oil, thereby allowing it to undergo sufficient centrifugal separation in the swirl chamber. Latulipe Eric et al. [8] added a porous diffuser at the bottom of the swirl chamber to reduce the flow velocity of the lubricating oil as it passes through. E. Timothy Pawl et al. [9] configured five small separators circumferentially distributed along the main axis to form an integrated unit, with each small separator having its own tangential swirl inlet. Zhang Xiaobin et al. [10] established four prediction models for the separation characteristics and two engineering prediction models for the resistance characteristics of dynamic oil-gas separators using dimensional analysis, enabling accurate evaluation of the separation and pressure drop performance of the device. Zhu Weibing et al. [11] established prediction models for the separation and resistance characteristics of a dynamic oil-gas separator using dimensional analysis. The separation efficiency was evaluated by the volumetric method, and the effects of various structural parameters on separation performance were investigated. Li Kening et al. [12] addressing the oil-gas deaeration requirements of aero-engine lubrication systems, proposed a novel dynamic oil-gas separator featuring a square inlet and a compact structure. By combining numerical simulation with experimental testing, they investigated the effects of flow velocity, oil volume fraction, and oil droplet size on the separation efficiency. Yang Jishen et al. [13] , addressing the difficulty of validating two-phase flow simulation results, designed a test scheme that closely resembles actual engine operating conditions and built a dedicated experimental setup. By combining numerical simulation with experimental testing, they analyzed the influence of key structural parameters on separation efficiency. Yang Xu et al. [14] utilized numerical simulation methods to investigate the pressure distribution patterns and primary sources of pressure loss within separators under different flow rates. Meanwhile, Wang Li et al. [15] designed a novel porous-plate oil gas separator structure and systematically examined its separation performance and pressure drop characteristics.

Under operating conditions characterized by high gas content in the return oil line, the separation efficiency of existing separators decreases significantly, making it difficult to supply lubricating oil of sufficient quality for the lubrication of transmission components. This can lead to component wear and even failure. To address this issue, this paper presents a two-stage oil gas separator, which achieves enhanced overall separation efficiency by subjecting the oil gas mixture to a secondary separation stage, thereby effectively resolving the aforementioned problems.

2. Structure of the Two-Stage Oil-Air Separator and the Separation Principle of the Wake Separator

The model investigated in this study is shown in Figure 1.The oil-gas mixture enters the separator through the oil return port. The wake separator structure at the oil return port can remove a portion of the bubbles from the mixture. And the remaining mixture enters the liquid storage separation chamber tangentially at a certain velocity, swirling along the wall. Under the influence of centrifugal force, the denser lubricating oil is forced toward the wall of the separation cylinder, moves downward along the wall, and is eventually discharged through the oil outlet pipe. The less dense air gathers toward the center under the combined action of centrifugal and centripetal forces, moves upward, and is finally discharged through the gas outlet pipe. Compared with the two-stage configuration, the single-stage dynamic oil-gas separator lacks the wake separator structure. The detailed comparison between the two is shown in Figure 2.

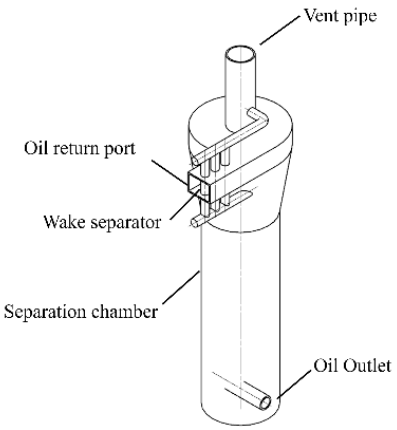


Figure 1 Structure of the two-stage dynamic oil-gas separator

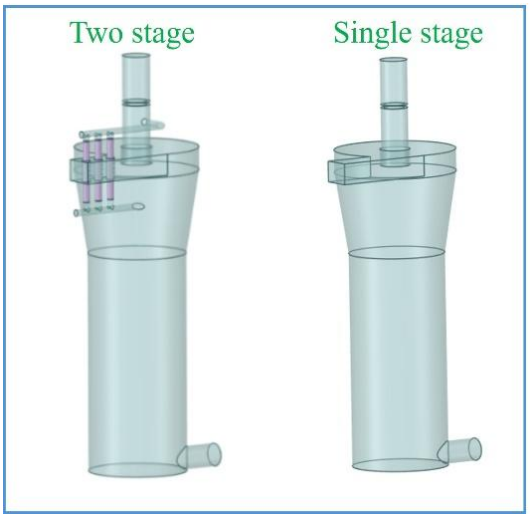


Figure 2 Schematic Diagram of Single-Stage and Two-Stage Oil-Air Separator Structure

As shown in Figure 3, the wake separator consists of one or more tubes with small holes (degassing holes). In this design, the wake separator typically adopts a configuration in which holes are drilled on the sidewall surface of the circular tube. The flow of the oil-gas mixture through the wake separator is illustrated in Figure 3, and its operating principle can be described as follows:

(1) The locations with small holes on the outer side of the circular tube can adsorb bubbles, and these holes serve to connect the bubbles.

(2) When airflow passes through the circular tube, the return oil flowing along the tube creates a low-pressure zone downstream of the tube. This low-pressure zone draws bubbles toward the downstream holes. When the airflow velocity inside the tube is sufficiently high, the static pressure inside the tube becomes relatively lower than that outside. As a result, bubbles are forced into the tube through the holes and subsequently expelled, ultimately eliminating them.

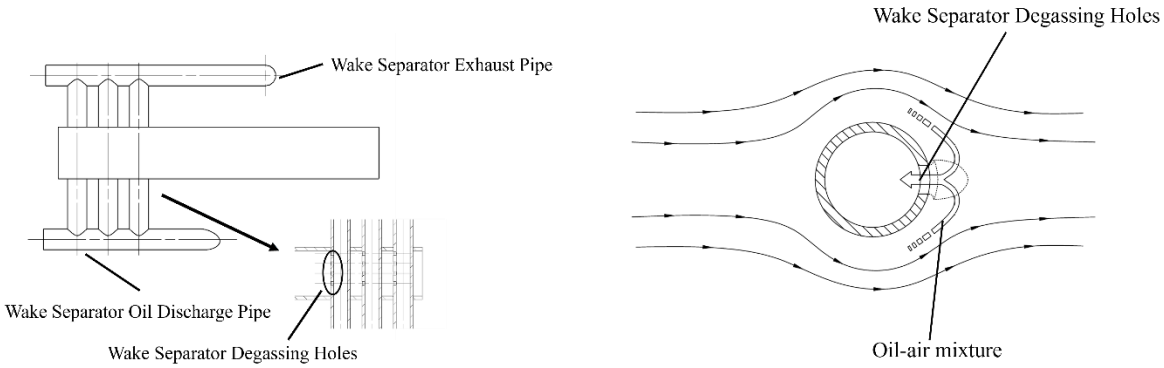


Figure 3 Schematic diagram of the wake separator structure

3. Numerical Method, Mesh, and Boundary Conditions

3.1 Computational Method and Boundary Conditions

The computational model adopted in this paper is the VOF (Volume of Fluid) model, and the turbulence model is the standard k-ε model. The working fluids in the simulation are aero-engine lubricating oil and air. The operating conditions for the calculation are shown in Table 1.

Table 1 Boundary Conditions and Physical Property Parameters

Parameter	Value
Inlet velocity (m/s)	4.3
Air outlet pressure (Pa)	101325
Lubricating oil outlet pressure (Pa)	101325
Temperature (℃)	120
Inlet lubricating oil flow rate (L/min)	30
Inlet air flow rate (L/min)	30
Lubricating oil density (kg/m^3)	972.2
Air parameters	ideal gas law

3.2 Computational Method and Boundary Conditions

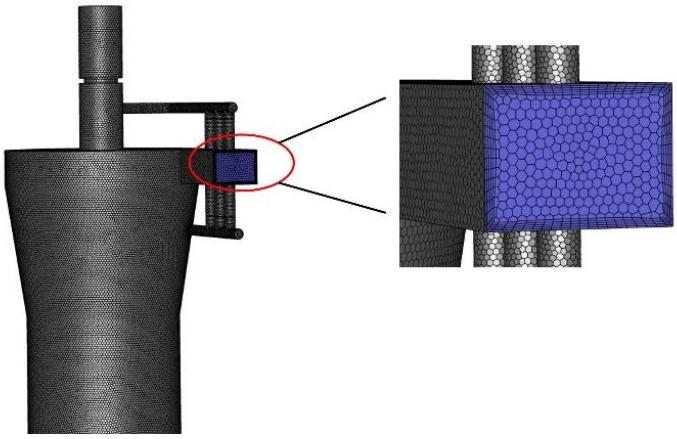


Figure 4 Computational grid and inlet boundary layer

First, the influence of grid density on the calculation results was investigated. The obtained results are presented in Table 2. To conserve computational resources, the G4 grid was selected for subsequent calculations.

Table 2 Effect of Different Grid Densities on Calculation Results

Grid	Grid Density	Pressure Drop /kPa	Separation Efficiency /%
G1	634568	16.2	99.03
G2	1574305	16.3	99.31
G3	2345212	16.7	99.45
G4	3515634	16.9	99.69
G5	4567585	17.2	99.71

3.3 Definitions

Evaluating the performance of an oil-gas separator requires a set of criteria. Currently, only two performance indicators are used in existing research: separation efficiency and pressure drop. This paper proposes three evaluation metrics for oil-gas separator performance, namely separation efficiency, pressure drop, and oil consumption ratio. The oil-gas separation efficiency characterizes the degree to which the oil and air are separated from the oil-gas mixture. The pressure drop represents the flow resistance loss of the oil-gas separator. The oil consumption ratio reflects the efficiency of oil recovery, the amount of oil consumed through the vent port.

Separation Efficiency is a critical parameter for evaluating the performance of a dynamic-pressure oil-air separator. It indicates the separator's ability to separate air from lubricating oil and, to some extent, reflects its effectiveness in reducing oil loss. The separation efficiency is defined as follows[16].

$$\eta = \frac{m_{inlet-g} - m_{oilout-g}}{m_{inlet-g}}$$

Where $m_{inlet\text{-}g}$ represents the mass flow rate of air at the inlet of the oil-air mixture, and $m_{oilout\text{-}g}$ represents the mass flow rate of air at the lubricating oil outlet.

Pressure Drop: Since the separator has two outlets, the pressure difference between the oil outlet and the inlet more accurately represents the pressure loss of the oil phase after passing through the separator.

$$\Delta P = P_{in} - P_{out}$$

Where P_{in} represents the inlet pressure of the oil-gas separator, and P_{out} represents the oil outlet pressure of the oil-gas separator.

According to the analysis of the calculation results, a portion of the lubricating oil is discharged along with the air through the vent pipe, resulting in oil loss. Therefore, in addition to separation efficiency, the oil loss through the vent pipe should also be taken into consideration, as it equally affects the performance of the oil-gas separator. The amount of oil lost through the vent pipe is quantified by the vent pipe oil consumption ratio defined as follows.

$$\eta' = \frac{m_{airout-o}}{m_{ilnet-o}}$$

Where $m_{airout\text{-}o}$ represents the oil mass flow rate at the air outlet, and $m_{inlet\text{-}o}$ represents the oil mass flow rate at the oil-gas mixture inlet.

Oil-gas ratio: The ratio of the oil volumetric flow rate to the air volumetric flow rate.

4. Analysis of Computational Results

4.1 Performance Analysis of the Initial Model and Comparison with the Single-Stage Model

This section primarily investigates the differences between the initial two-stage separation model and the single-stage separation model, with a comparative analysis conducted in terms of separation efficiency and pressure loss characteristics. At a lubricating oil flow rate of 30 L/min, the volumetric ratios of inlet oil to air were varied to 1:1, 1:2, 1:3, and 1:4. The computational results are presented as follows.

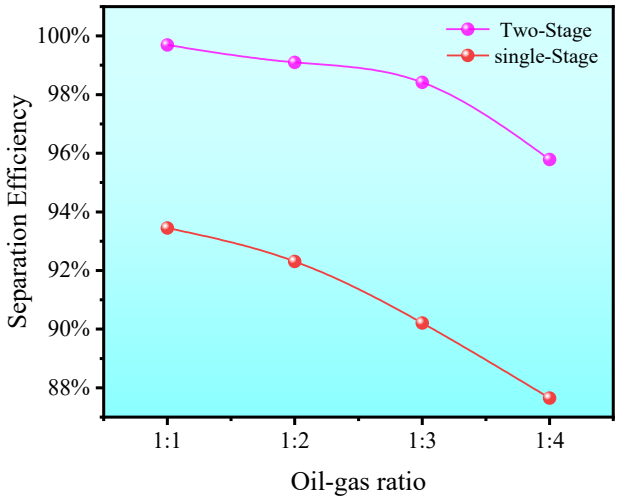


Figure 5 Separation efficiency of the two-stage and single-stage oil-gas separators

As shown in Figure 5, the separation efficiency of the two-stage oil-gas separator is superior to that of the single-stage separator. With an increase in air content, the separation efficiencies of both separators decrease; however, the separation efficiency of the single-stage separator declines at a steeper rate. At an oil-gas ratio of 1:4, the separation efficiency of the single-stage separator drops to 87.65%, while that of the two-stage separator remains at 95.79%. This indicates that the wake separator plays a significant role under high gas volume fraction operating conditions.

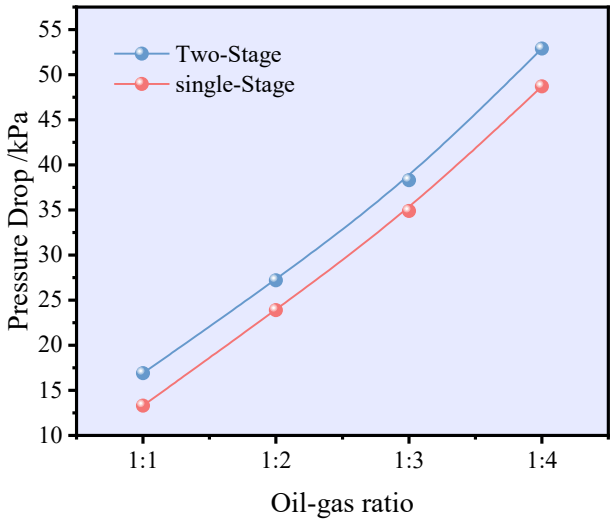


Figure 6 Pressure drop of the two-stage and single-stage oil-gas separators

As shown in Figure 6, the pressure drop of the two-stage oil-gas separator is greater than that of the single-stage separator. Under the same operating conditions, the pressure drop of the two-stage separator is 3–4 kPa higher than that of the single-stage version. This is because the two-stage oil-gas separator incorporates an additional wake separator structure, which essentially adds a flow resistance element and consequently increases pressure loss. As the oil-gas ratio varies from 1:1 to 1:4, the pressure drop increases with rising air content.

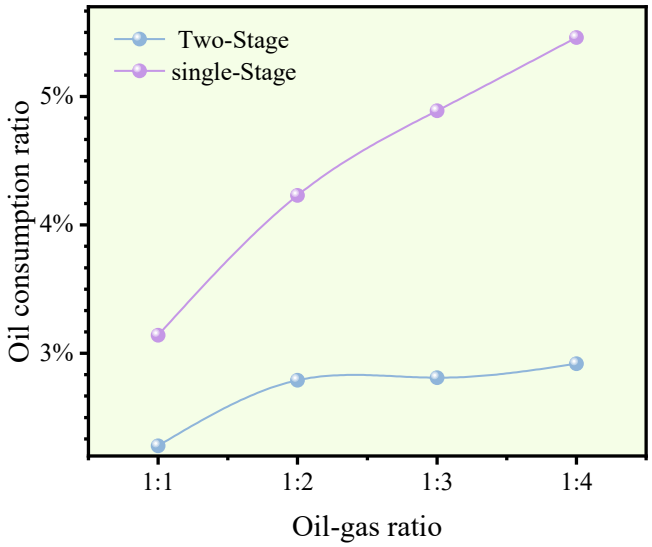


Figure 7 Oil consumption ratio of the two-stage and single-stage oil-gas separators

As shown in Figure 7, with the decrease in oil-gas ratio (i.e., the increase in gas content), the oil consumption ratios of both the two-stage and single-stage oil-gas separators gradually increase. This is because, given a fixed inlet area, the total volumetric flow rate at the inlet increases, leading to higher flow velocities of both the inlet oil and air. Meanwhile, as the oil-gas ratio decreases, the gas content rises, resulting in a greater amount of air carrying oil out through the vent pipe. Comparing the oil consumption ratios of the two-stage and single-stage separators, the two-stage separator exhibits a lower oil consumption ratio. This is because the wake separator has already removed a portion of the air before it enters the vent pipe, thereby reducing the air flow rate entering the separation chamber.

Based on the three performance indicators—separation efficiency, pressure drop, and oil consumption ratio—the two-stage oil-gas separator outperforms the single-stage version in terms of separation efficiency and oil consumption ratio. Regarding pressure drop, the single-stage separator clearly exhibits a lower pressure drop and thus less flow loss; however, the difference between the two configurations is only 3–4 kPa, which is relatively modest. Overall, the two-stage oil-gas separator achieves superior separation performance, and the additional pressure loss of 3–4 kPa remains within an acceptable range.

4.2 Effect of Orifice Size on Separation Performance

In this paper, an oil-gas ratio of 1:3 is taken as the design point operating condition. For this design condition, the orifice diameter is varied to investigate its effect on the performance of the two-stage oil-gas separator. The calculation results are presented in Table 3.

Table 3 Comparison of separation efficiency for different orifice diameters

orifice diameters	0.5mm	1mm	1.5mm	2mm
separation efficiency	98.10%	98.42%	98.93%	98.36%
oil consumption ratio	3.45%	2.81%	2.75%	3.6%
pressure drop	44.1 kPa	38.3kPa	38.4kPa	38.9 kPa

As shown in Table 3, under the design point operating condition, the separation efficiencies for all four orifice diameters are above 98%, among which the 1.5 mm orifice achieves the highest separation efficiency and the lowest oil consumption ratio. The pressure drop for the 0.5 mm orifice is the largest, approximately 6 kPa higher than that of the other three configurations, while the pressure drops for the remaining three orifice sizes are essentially identical. These results indicate that the 1.5 mm orifice yields the best overall performance. The separation effect of the wake separator will be discussed in further detail below

The effect of orifice diameter will be evaluated below from three aspects: the separation efficiency of the wake separator, the volumetric flow rate of separated gas, and the flow rate of entrained oil consumed.

The wake separator structure consists of three tubes with degassing holes. Taking the oil return port as a reference, the pipes are sequentially named Pipe 1, Pipe 2, and Pipe 3. The degassing efficiency is defined as the ratio of the gas flow rate entering the vent pipe through the wake tube to the gas flow rate entering the wake tube.

As shown in Figure 9, as the orifice diameter of the wake separator increases, the volumetric flow rate of gas separated by each tube also increases. A larger volumetric flow rate of separated gas is beneficial for secondary separation. Among the configurations, the wake separator structures with orifice diameters of 1.5 mm and 2 mm exhibit better gas separation performance. As shown in Figure 8, for tubes at the same position (Tube 1 and Tube 2), separation efficiency decreases with increasing orifice diameter. For Tube 3, however, separation efficiency first increases and then decreases as the orifice diameter increases. Overall, the wake separator structures with 1.5 mm and 2 mm orifices demonstrate better separation efficiency. Compared with the 2 mm configuration, the 1.5 mm structure separates a slightly lower volumetric flow rate of gas, but achieves higher separation efficiency per tube. Next, the performance of the orifice will be further evaluated based on the oil consumption of the wake separator.

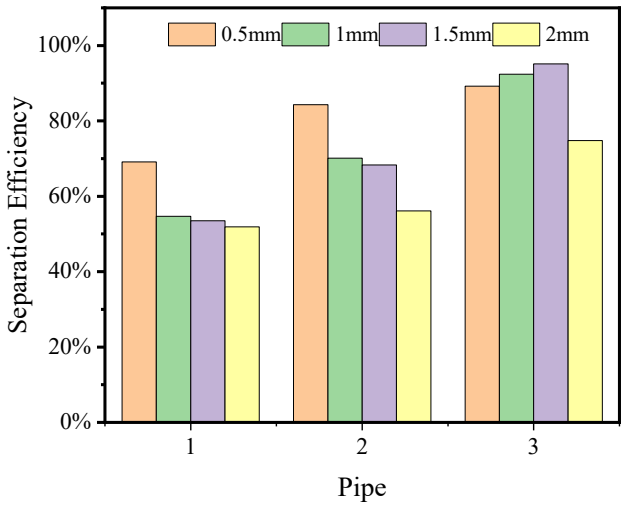


Figure 8 Separation efficiency of tubes with different wake separator configurations

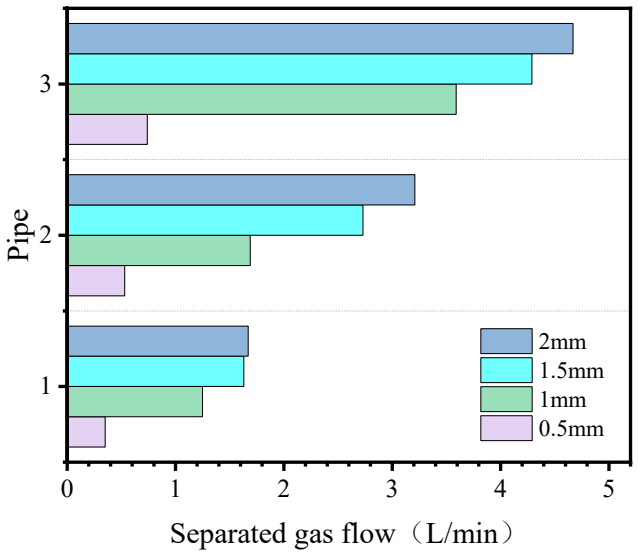


Figure 9 Separated air flow rate of tubes with different wake separator configurations

As shown in Figure 10, as the orifice size of the wake separator increases, the volume of oil consumed by the wake separator first decreases and then increases. Among the configurations, the wake separator structures with orifice diameters of 1 mm and 1.5 mm exhibit relatively low oil consumption. The oil-gas distribution within the wake separator can also be observed from the contour plots in Figure 11. In the 0.5 mm wake separator, the amount of oil entering the vent line is the largest, whereas the 1.5 mm wake separator results in the least amount of oil escaping into the vent.

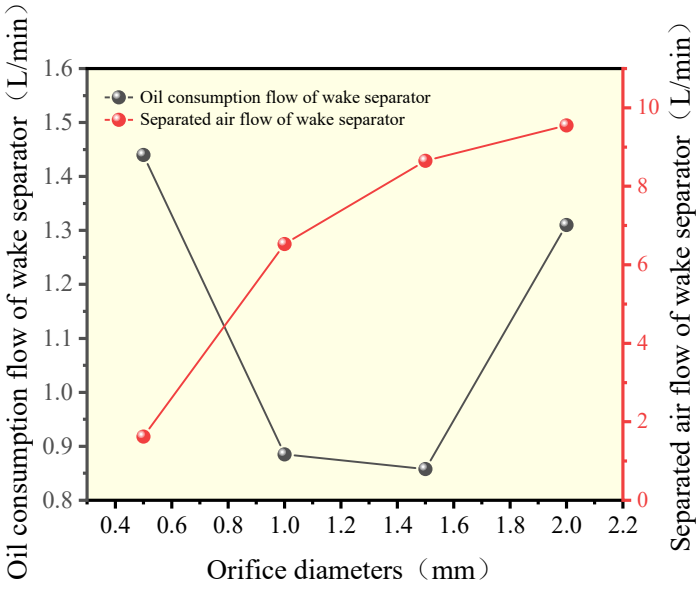


Figure 10 Separated air flow rate and oil consumption flow rate for different wake separator configurations

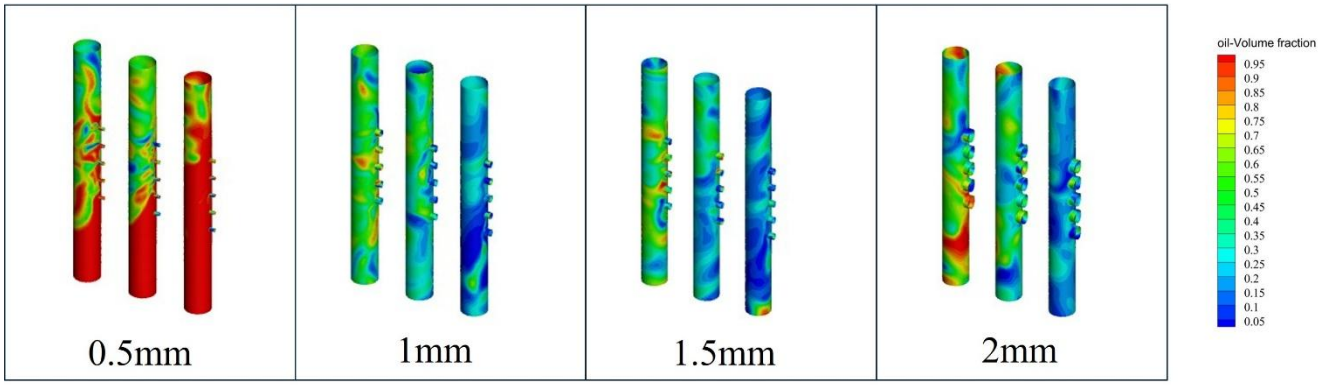


Figure 11 Oil-gas distribution in the wake separator for different orifice diameters

Based on a comprehensive evaluation of tube separation efficiency, air separation flow rate, and oil consumption flow rate of the wake separator, the 1.5 mm orifice configuration demonstrates the best overall performance among the four designs. Consequently, the 1.5 mm orifice is selected as the final wake separator structure. Multi-condition simulation calculations and analyses were then performed on the optimized geometry, and the results are presented in Table 4.

Table 4 Comparison before and after orifice structure optimization

	1mm orifice diameters			1.5mm orifice diameters		
oil-gas ratio	separation efficiency	oil consumption ratio	pressure drop	separation efficiency	oil consumption ratio	pressure drop
1:1	99.69%	2.28%	16.9kPa	99.87%	2.3%	16.4 kPa
1:2	99.10%	2.79%	27.2kPa	99.67%	2.7%	27.3 kPa
1:3	98.42%	2.81%	38.3kPa	98.93%	2.75%	38.4kPa
1:4	95.79%	2.92%	52.9kPa	96.82%	2.76%	52.8 kPa

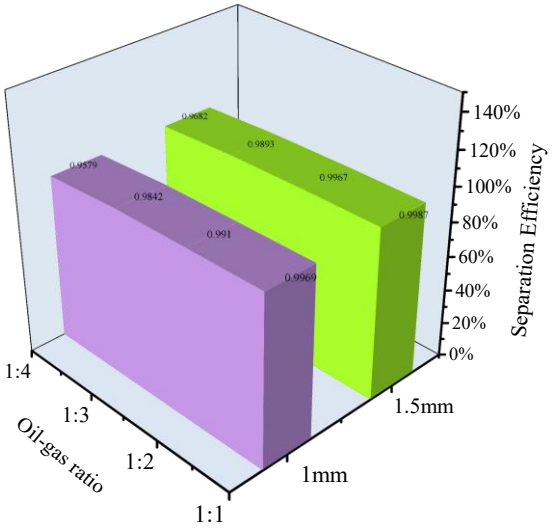


Figure 12 Comparative analysis of separation efficiency for 1 mm and 1.5 mm orifices

As shown in Table 4, among the three performance indicators of the oil-gas separator, separation efficiency is the most significantly affected by the change in orifice diameter. It can be observed from Figure 12 that under the same operating conditions, the orifice size has little to no effect on the oil consumption ratio or pressure drop, but it does improve separation efficiency. The higher the gas content, the more pronounced the improvement in separation efficiency due to the orifice size variation.

4.3 Effect of Inlet Area on Separation Performance

Based on the previous investigation, the structure with a 1.5 mm orifice diameter was selected as the baseline to explore the effect of inlet area on separator performance under the design point condition. The modification of the inlet area is illustrated in the figure below. Only the height of the inlet was varied, while the width remained unchanged. According to the model geometry, the inlet area was increased up to 1.75 times its original size.

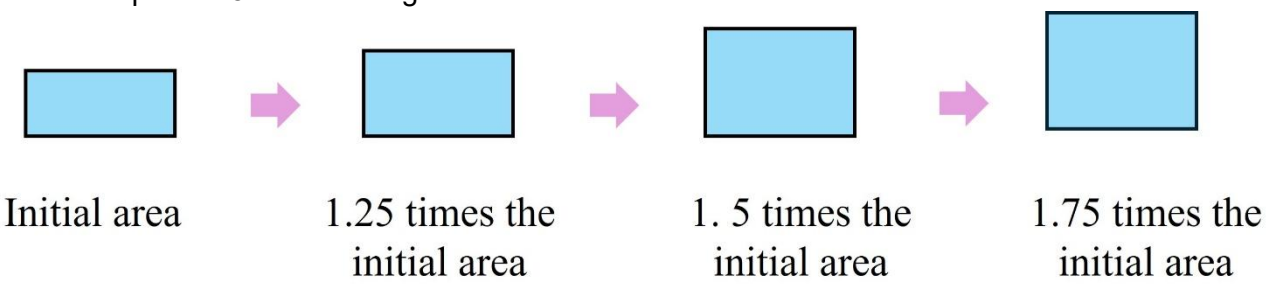


Figure 13 Modification of the inlet area

Figures 14 and 15 analyze the influence of inlet area on the performance of the oil-gas separator from three aspects: separation efficiency, oil consumption ratio, and pressure drop. In terms of separation

efficiency, as the inlet area increases, the separation efficiency tends to rise, with the variation not exceeding 1%. This indicates that the inlet area has a minor effect on separation efficiency. Regarding the oil consumption ratio, as the inlet area increases, the oil consumption ratio first increases and then decreases. The variation in oil consumption ratio among the different inlet areas is also less than 1%, suggesting that the inlet area has little impact on this metric as well.

With respect to pressure drop, as the inlet area increases, the pressure drop gradually decreases, and the rate of decrease diminishes. Among the four inlet areas tested, the configuration with 1.75 times the original inlet area exhibits the smallest pressure drop.

Overall, the 1.75× inlet area configuration demonstrates the best comprehensive performance. Therefore, subsequent multi-condition simulation analyses are performed on the structure with an inlet area of 1.75 times the original.

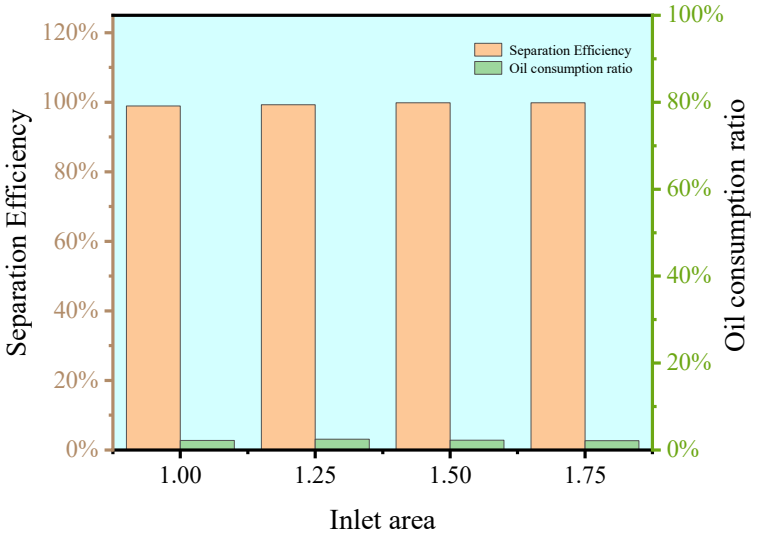


Figure 14 Separation efficiency and oil consumption ratio

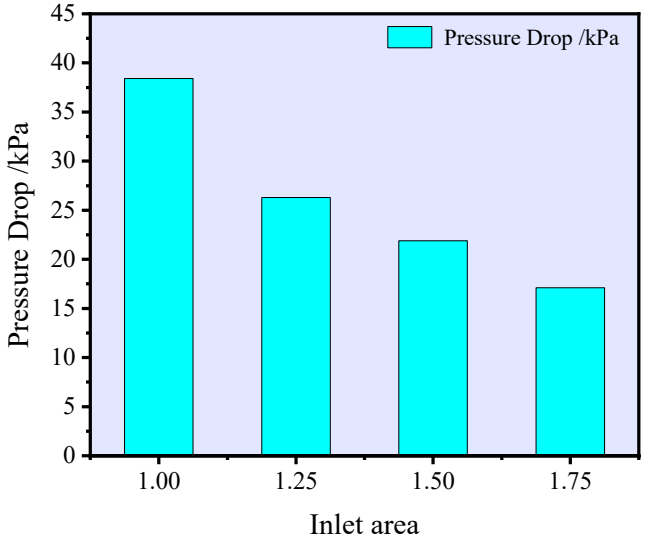


Figure 15 Variation of pressure drop with inlet area

4.4 Multi-Operating-Condition Analysis of the Optimized Structure

Based on the investigation of wake separator orifice size in Section 4.2, the configuration with a 1.5 mm orifice was determined to achieve the best separation performance. Through the study of inlet area in Section 4.3, the structure with 1.75 times the original inlet area was found to yield the lowest pressure drop. Consequently, the model offering the best separation efficiency and the model with the minimum pressure loss were identified and subjected to multi-operating-condition simulation studies.

As shown in Figure 16, the optimized two-stage oil-gas separator achieves higher separation efficiency than the initial design, with the improvement being particularly pronounced under high gas volume fraction conditions. The optimized separator effectively addresses the issue of low separation

efficiency encountered under high gas content operating conditions.

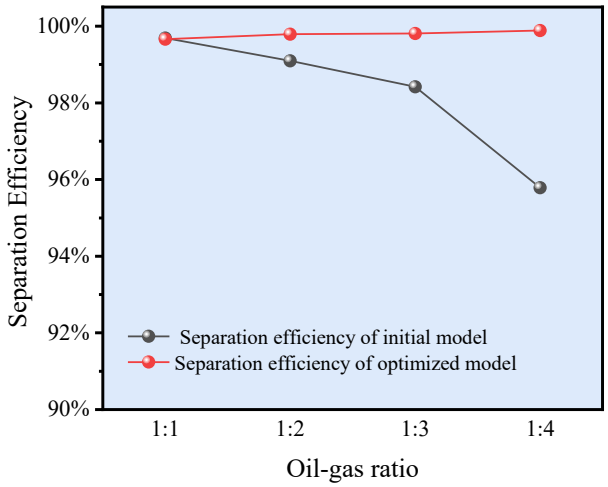


Figure 16 Comparison of separation efficiency between the optimized model and the initial mode

As shown in Figure 17, the oil consumption ratio of both the optimized and initial oil-gas separators ranges between 2% and 3%. However, under the same operating conditions, the optimized separator structure exhibits a lower oil consumption ratio, indicating that less lubricating oil is consumed.

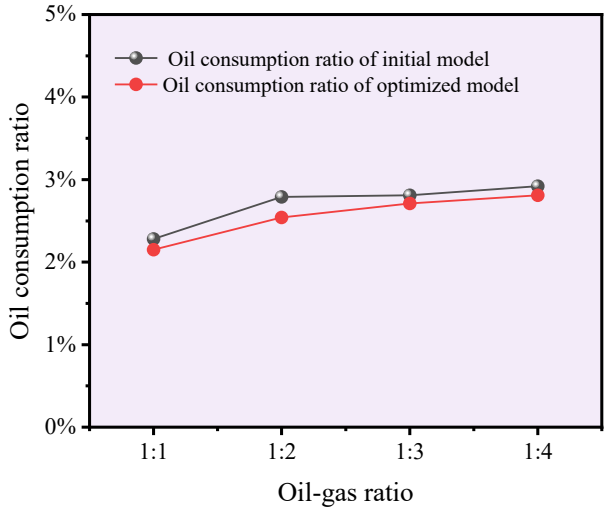


Figure 17 Comparison of oil consumption ratio between the optimized model and the initial model

As shown in Figure 18, under the same operating conditions, the pressure drop of the optimized oil-gas separator structure is significantly reduced. As the gas content increases and the oil-gas ratio varies from 1:1 to 1:4, the pressure drop gradually increases. The pressure drop variation for the optimized structure is approximately 10 kPa, whereas that of the initial structure is about 40 kPa. This demonstrates that the optimized oil-gas separator achieves a marked improvement in reducing pressure loss.

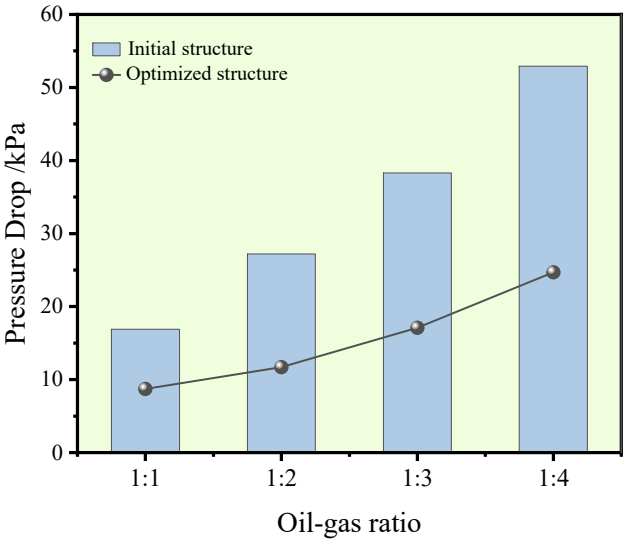


Figure 18 Comparison of pressure drop between the optimized model and the initial model

As shown in Figure 19, as the oil-gas ratio varies from 1:1 to 1:4, the oil content inside the wake separator gradually decreases while the air content increases. The highest oil content is observed in the first tube of the wake separator, and the lowest oil content is found in the third tube.

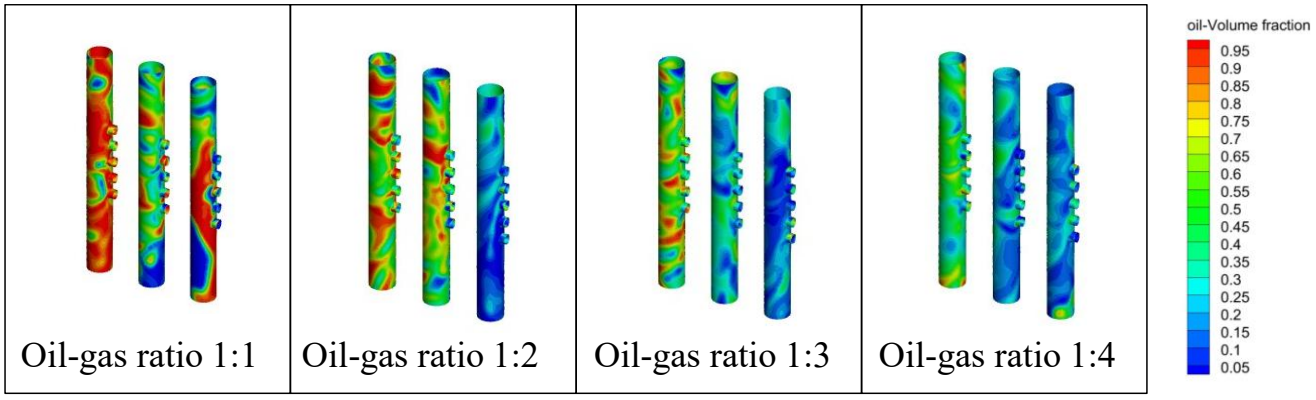


Figure 19 Oil-gas distribution in the optimized wake separator

5. Conclusion

(1) This paper proposes separation efficiency, oil consumption ratio, and pressure drop as evaluation metrics for assessing the performance of oil-gas separators. By comparing the performance of the two-stage and single-stage oil-gas separators, the results show that the two-stage separator outperforms the single-stage separator in terms of separation efficiency and oil consumption ratio, while the single-stage separator exhibits better pressure drop performance.

(2) For the initial two-stage oil-gas separator model, the separation efficiency gradually decreases with increasing gas content. To improve its separation performance under high gas content operating conditions, the separation effectiveness of the wake separator with different orifice diameters was investigated. It was ultimately determined that the wake separator configuration with a 1.5 mm orifice diameter exhibits the best separation performance.

(3) Based on the wake separator model with a 1.5 mm orifice diameter, the influence of different inlet areas on the performance of the two-stage oil-gas separator was investigated. The results show that the configuration with 1.75 times the original inlet area achieves the best overall performance and the lowest pressure loss.

(4) Multi-operating-condition simulation analysis was conducted on the optimized two-stage oil-gas separator structure. The results show that the optimized two-stage oil-gas separator exhibits improved separation efficiency under high gas content conditions, with all separation efficiency values exceeding 99%. The oil consumption ratio is also lower, indicating reduced lubricating oil loss. Furthermore, the pressure drop is decreased, resulting in lower flow resistance loss.

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