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Design of Separation Method for Floccules in Condensate Oil from Tight Gas Reservoirs

Jiang Yao, Rong Zong, Yuquan Jing and Quan He

Northwest Sichuan Gas District, Southwest Oil & Gasfield Company, PetroChina, Mianyang 621700, China

Abstract: Floccule contamination in condensate oil is a widespread and severe problem. Conventional separation processes fail to achieve thorough separation and cannot meet industrial requirements. To address this issue, this paper designs a separation scheme tailored for floccules in condensate oil, thereby solving the critical problems of substandard condensate oil quality and frequent product returns. By investigating and comparing various separation schemes, this study determines the use of a decanter centrifuge as the separation equipment and completes the design of the separation scheme and device. Through principle experiments, the influences of material properties and rotating speed on centrifugal separation performance are analyzed. The flow field of the centrifuge is investigated using the finite element method. This research not only improves the separation efficiency of condensate oil and oil product quality but also holds great significance for enhancing the economic benefits of oil and gas fields.

Keywords: Condensate Oil; Separation; Decanter Centrifuge; Fluid Simulation.

1. Introduction

Floccule contamination in condensate oil is prevalent and severe. Therefore, it is imperative to conduct research on effective separation schemes for condensate oil containing floccules, improve the quality of condensate oil, and prevent product returns caused by excessive floccule content or water content.

At present, the main separation methods for condensate oil include gravity sedimentation, membrane filtration separation, chemical flocculation, electro-dehydration, air flotation separation, and centrifugal separation.1)Gravity sedimentation is based on density differences between phases. After a period of time, the oil-water mixture reaches an equilibrium state and stratifies inside the separator: the gas phase is at the top, the oil phase in the middle, and the heavy water phase settles at the bottom following Stokes' law[1]. Common three-phase gravity settling equipment mainly consists of an inlet distributor, a rectifying plate group, and internal components.2)Membrane filtration separation uses a selective filtration membrane as the separation medium. A driving force is applied across the membrane, pushing part of the mixture through the membrane to complete separation. Membrane separation includes dead-end filtration and cross-flow filtration. Dead-end filtration relies on gravity but tends to form filter cakes and cause clogging. Cross-flow filtration uses shear force, which reduces cake formation and extends membrane service life[2]. 3)Chemical flocculation involves adding flocculants that hydrolyze into positively charged micelles, reacting with negatively charged substances in the mixture to form flocs, which are then removed by gravity sedimentation or other methods[3-5], However, flocculants increase costs and cause secondary pollution in the collected oil and separated water[6-8]. Flocculants are classified into inorganic, organic, and composite flocculants. 4)Electro-dehydration uses an electric field to aggregate and grow water droplets, rupture the oil-water interface film, and finally achieve phase separation. Common electric field types include direct current (DC), alternating current (AC), combined AC/DC, and pulsed electric fields.5)Air flotation separation injects dense microbubbles into water, which collide and adhere to solid impurity particles or liquid droplets to form floc-bubble aggregates with a bulk density lower than water. These aggregates float to the surface under buoyancy and are removed as scum[9].6)Centrifugal separation realizes phase separation in a high centrifugal force field. According to separation principles, centrifuges are divided into sedimentation and filtration types[10]. Filtration centrifuges use internal filter media to separate materials under centrifugal motion. Sedimentation centrifuges separate materials based on different settling velocities of phases in the centrifugal force field, mainly including disc-stack centrifuges and decanter centrifuges. A disc-stack centrifuge separates solid and liquid phases using density differences during high-speed rotation of the disc stack[11]. A decanter centrifuge uses a screw conveyor with differential rotation to push separated solid and liquid phases to overflow outlets at the large and small ends of the centrifuge, completing two-phase separation [12].

2. Optimization and Validation of a Separation Scheme for Floccules in Condensate Oil

2.1. Adaptability Comparison of Condensate Oil Separation Methods

(1) Gravity Sedimentation

Advantages: Extremely low operation difficulty, no complex equipment required, only a settling tank can be completed; simple operation process, manual judgment of discharge timing. Disadvantages: Manual operation cannot prevent flocs from entering the storage tank with the oil phase, and slight disturbance will mix flocs with oil, reducing the purity of the oil phase; low separation efficiency, long settling time, unable to handle fine flocs, and difficult to independently meet industrial standards.

(2) Membrane Filtration Separation

Advantages: Membrane filtration can well filter flocs in condensate oil without secondary pollution. Disadvantages: Moderate operation difficulty, but when the floccule content is high, it will adhere to the membrane, easily block the membrane module, and manual regular backwashing is required; not suitable for large-scale continuous production; poor water separation effect.

(3) Chemical Flocculation

Advantages: Good separation effect, can effectively remove flocs. Disadvantages: It will cause secondary pollution of oil products, and the purified oil products may be polluted by flocculants, leading to disqualification; substandard environmental protection, difficult treatment of waste products; difficult operation, requiring strict control of flocculant type and dosage.

(4) Electro-dehydration

Advantages: Fast separation speed, greatly reducing the water content in condensate oil, no secondary pollution. Disadvantages: Mainly separating water in condensate oil, the separation effect on flocs is general, and flocs may block electrodes; high-voltage equipment needs additional protection to avoid accidents.

(5) Air Flotation Separation

Advantages: Good separation effect, can effectively separate flocs and water in condensate oil, not easy to cause secondary suspension of flocs. Disadvantages: Strict requirements on floccule particle diameter, difficult control of bubble diameter, great impact on separation effect, difficult treatment of subsequent scum, and special equipment required.

(6) Centrifugal Separation

Advantages: Good separation effect, can effectively separate flocs in condensate oil and reduce the water content of oil products at the same time; no secondary pollution, can adapt to large-scale production; stable equipment operation and high separation efficiency. Disadvantages: High-speed rotating machinery, which needs protective measures to avoid explosion during operation; high floccule content needs pretreatment to avoid blockage; large equipment volume and large floor space; regular maintenance is required, and high requirements for operators. Table 1 is the comparison of advantages and disadvantages of different separation methods.

Table 1. Comparison of condensate oil separation methods

Method	Advantages	Disadvantages
Gravity Sedimentation	Simple method, low cost	Unreliable quality, unstable performance
Membrane Filtration Separation	Simple operation, strong selectivity	Relatively high cost, weak pollution resistance and corrosion resistance, poor water separation effect
Chemical Flocculation	Low dosage, high efficiency	Insufficient stability, easy to cause secondary pollution
Electro-dehydration	High dehydration efficiency, flexible operation	Poor ability to separate flocs
Air Flotation Separation	Good separation effect, less likely to cause secondary suspension of flocs	Relatively high cost, troublesome subsequent treatment of scum
Centrifuge Separation	High separation efficiency, fast processing speed, adaptable to complex working conditions	High equipment cost, high operating noise

2.2. Principle Experiment Verification

(1) Sedimentation Test

The samples collected from the wellhead were subjected to precipitation test, and the natural precipitation test for 1 ~ 60 minutes was carried out as shown in Fig.1. It is found that the separation effect can be achieved by natural sedimentation for 30 minutes. However, from the local amplification diagram, it can be seen that the separation effect of gravity natural sedimentation is not ideal because the flocs are suspended at the water interface or even embedded in the condensate oil, and the oil, water and flocs cannot be completely separated. The separation effect of gravity natural sedimentation is not ideal, and oil, water and flocs cannot be completely separated.

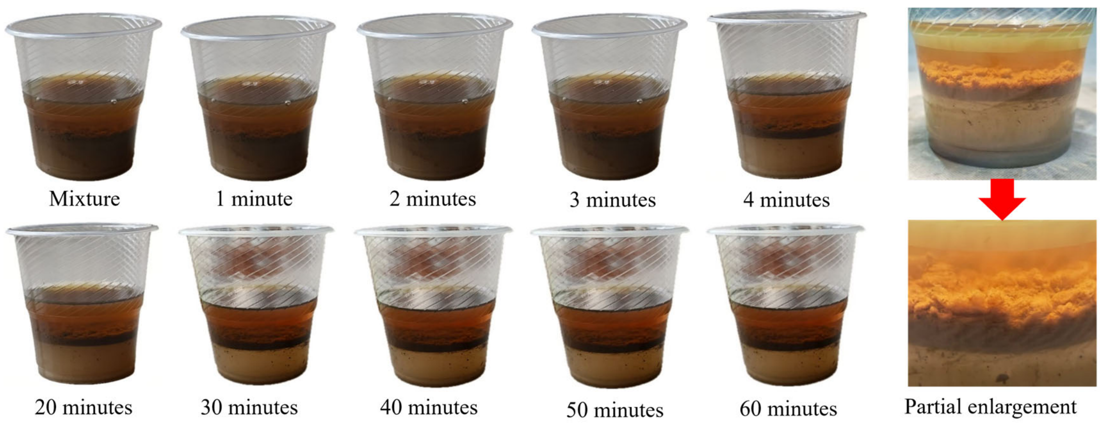
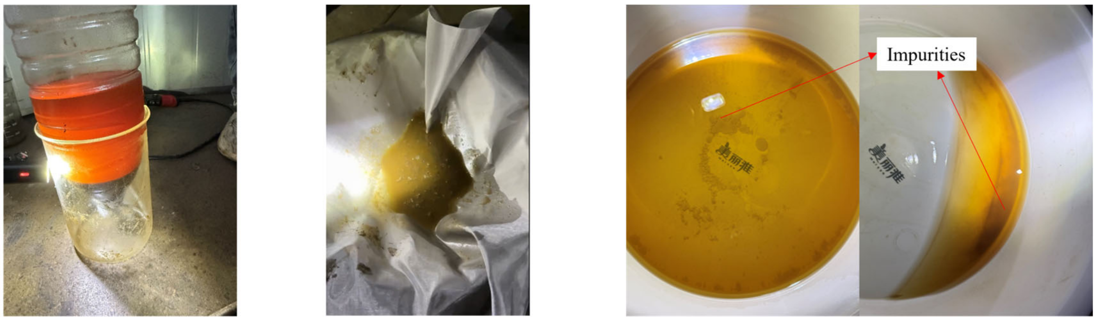


Figure 1. Natural sedimentation test

(2) Filter Screen Filtration Experiment

The 100 mesh, 200 mesh, 300 mesh, 600 mesh and 1200 mesh filter experiments were carried out, as shown in Figure 2. Filtration experiments were carried out on the samples under the same operating conditions to observe the clarity of the filtrate, the retention of impurities and the liquid flow performance of the filter. The experimental results show that the sample can filter most of the floccules through a 300-mesh filter, but there are still a small number of fine floccules that cannot be filtered. Increasing the mesh number of the filter can improve the filtration effect, but using a higher mesh filter, it is found that the liquid passability is poor, and it cannot be filtered by gravity alone. It is necessary to use suction tools to assist, which cannot meet the on-site transportation process of oil production.



Sample before filtration Filtered with 300-mesh screen Filtration effect

Figure 2. Filter screen filtration experiment

(3) Centrifugal Separation Experiment

Centrifugal separation experiments were conducted using a laboratory centrifuge to investigate the effect of rotational speed on separation efficacy. Tubes 1, 2, and 3 contained samples subjected to centrifugation. Tube 4 contained a sample of the oil layer after natural sedimentation. Tube 5 contained a sample of the oil layer after centrifugation of Tube 3. The experimental results are presented in Figure 3.

When the rotational speed is below 200 rpm, the oil layer after centrifugation remains relatively turbid, and the floccule phase is mixed with the aqueous phase. At 250 rpm, the oil phase is basically separated after centrifugation, whereas the floccule phase and aqueous phase are still mixed. When the rotational speed exceeds 300 rpm, the oil phase is fully separated, and the floccule phase is also clearly separated from the aqueous phase. These results indicate that centrifugal separation can effectively separate floccules, water and oil from the condensate.

Based on the above adaptability analysis and fundamental experiments of condensate separation, it is verified that centrifugal separation is a feasible and effective method for treating condensate floccules in tight gas reservoirs.

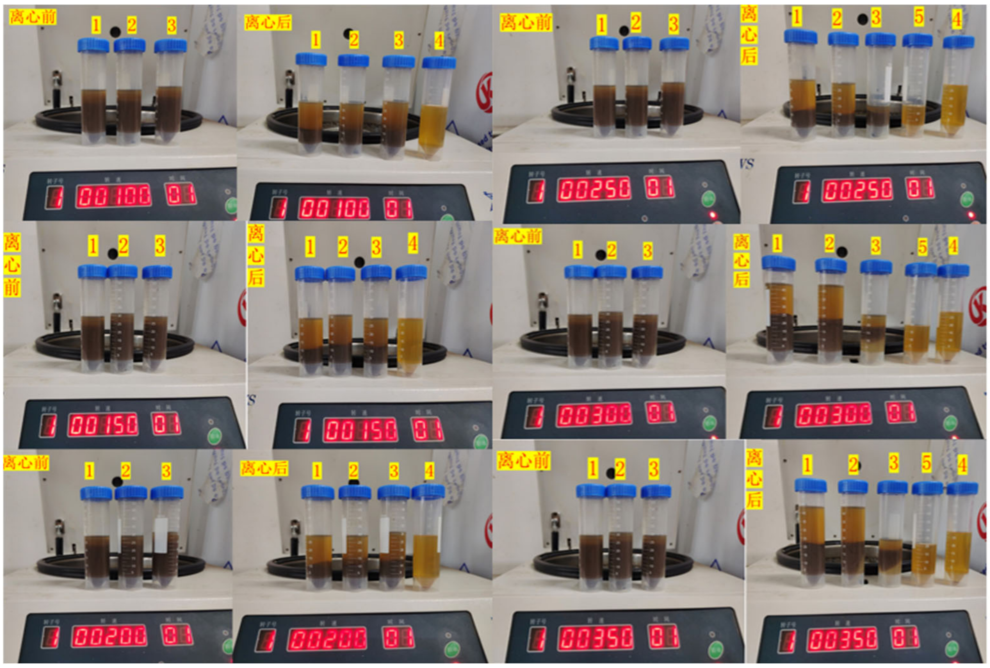


Figure 3. Separation effect at 100-350 r/min

3. Separation Scheme Design

3.1. Scheme Design

Materials enter the conditioning skid, are heated and cleaned in the conditioning tank of the conditioning skid, and are fully stirred. The conditioned materials are transported to the two-phase high-speed deoiling decanter centrifugal separation skid through the discharge pump. Condensate oil materials are transported to the feeding chamber in the mandrel of the screw unloader through the feeding pipe, and enter the outer bowl stably and quickly through the uniformly distributed discharge holes. The sludge-water phase is temporarily stored in the water storage tank for external transportation; qualified oil phase is extracted by the centripetal pump for collection and external transportation. The process flow is shown in Fig. 4.

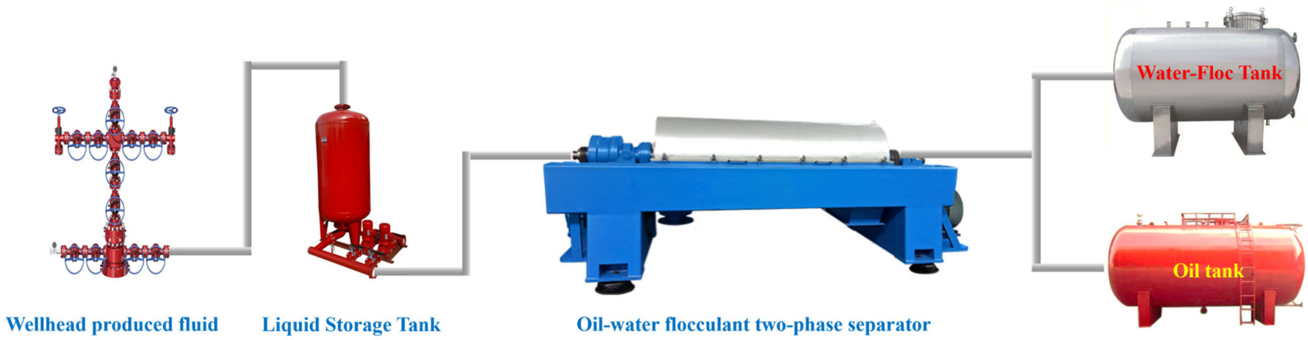


Figure 4. Process flow diagram

3.2. Device Design

(1) Working parameters

The ratio of centrifugal force to gravity force of the separated material in the centrifugal field is called separation factor Fr[13] . The separation factor is a core performance indicator for decanter centrifuges, directly determining the intensity of the centrifugal field. The calculation formula is:

$$F_r = \frac{F_c}{G} = \frac{m\omega^2 r}{mg} = \frac{\omega^2 r}{g} \tag{1}$$

Considering the material properties, the maximum separation factor is 3635, the bowl diameter is determined to be 450 mm, the maximum speed is determined to be 3800 r/min according to the formula, and the rated speed is 3400 r/min.

The required on-site processing capacity is specified as 5 m^3/h. The throughput calculation formulas are:

$$Q_f = v_s \cdot \Sigma \tag{2}$$

$$v_s = \frac{d_c^2(\rho_s - \rho_L)g}{18\eta} \tag{3}$$

$$\Sigma = \frac{\pi L\omega^2}{g} \cdot \frac{(r_2^2 - r_1^2)}{\ln(r_2 / r_1)} \tag{4}$$

Based on these calculations, the average processing capacity falls within the range of 4–6 m^3/h, satisfying the site requirements.

(2) Structural parameters

Bowl length is determined according to the length-diameter ratio. The selection of length-diameter ratio should comprehensively consider the characteristics of the suspension to be treated and the constraints in the manufacturing process, and cannot be increased indefinitely . For this design, an L/D ratio of 4.3 was selected. With a bowl diameter of 450 mm, the total bowl length is therefore 1940 mm.

The half-cone angle of the bowl is a key parameter of the bowl, which affects the separation effect of the whole decanter centrifuge. The larger the half-cone angle, the greater the power required for pushing, and an excessively large half-cone angle will cause the centrifuge to fail to push slag. In this paper, the half-cone angle is 8°.

he length of the cylindrical section of the bowl is calculated according to the formula[14]:

$$L_1 = r_2(2\frac{L}{D} - \frac{1-K_3}{\tan\alpha}) \tag{5}$$

Where K3 = 0.65. Based on this formula, the cylindrical section length is determined to be 1380 mm, and the conical section length is 560 mm. An excessively large helix angle of the scroll flights can lead to material blockage. Typical helix angles range from 4° to 6°. A helix angle of 5° was selected. The pitch, S, is calculated using $S = \pi D\tan\beta$. For this decanter centrifuge, the pitch is 124 mm.

(3) Material Selection

In the working state of the drum, to withstand the centrifugal pressure from the material and the centrifugal force of its own quality, the material is SAF2304 duplex stainless steel, which is manufactured by centrifugal casting. The contact wear between the screw conveyor and the material is large. Under the condition of ensuring strength, it is necessary to have certain wear resistance and prolong the service life. The spiral core tube material is SAF2304 duplex stainless steel, which is manufactured by centrifugal casting. The spiral blade material is 304 stainless steel, and the wear-resistant alloy sheet is used for welding treatment. The end cap shaft is a key component of power transmission, which needs to have a certain strength to ensure the stability of the equipment under high speed operation. The material is SAF2304 duplex stainless steel, which is manufactured by centrifugal casting.

In summary, the design and operational parameters of the decanter centrifuge are listed in Table 2, and the three-dimensional model is shown in Figure 5.

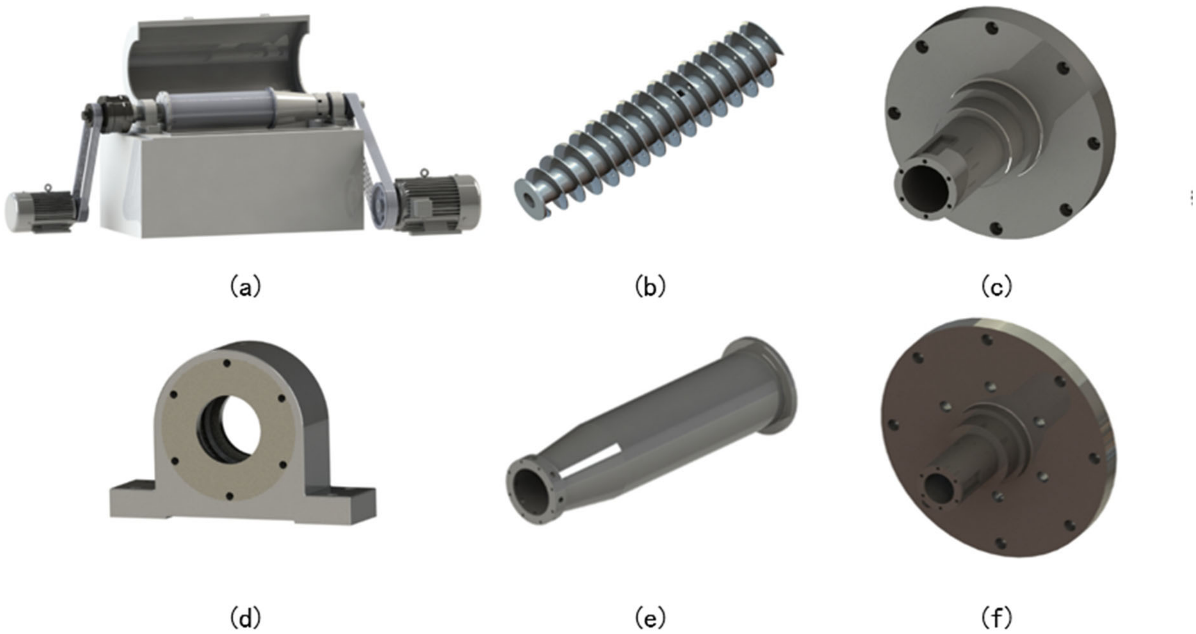


Figure 5. 3D model of the assembly(a) and 3D models of the main components(b-f)

Table 2. Parameter table of decanter centrifuge

Name	Value	Name	Value
Effective diameter of bowl (mm)	450	Diameter of screw core barrel(mm)	200
Length of cylindrical section of bowl (mm)	1380	Lead of screw blade (mm)	124
Length of conical section of bowl (mm)	560	Average processing capacity (m³/h)	4-6
Thickness of bowl (mm)	18	Thickness of screw core barrel (mm)	20
Half cone angle of bowl (°)	8	Differential speed (r/min)	30
Maximum design speed (r/min)	3800	Rated design speed (r/min)	3400

4. Multiphase Flow Separation Simulation Analysis

The multiple reference frame MRF (Multiple Reference Frame) method is used in the simulation. The flow area is defined as the fluid area. The interface surface is set between the screw and the drum to realize the differential rotation between the drum and the screw. The differential speed between the drum and the screw is 30 r / min. The inlet uses the speed inlet, which is perpendicular to the feed inlet, and the processing capacity is 5m3 / h ; both slag outlet and liquid outlet are defined as outflow. The operating parameters and physical parameters are shown in Table 3 and Table 4.

Table 3. Operating parameters

Parameter	Value
Bowl speed(r/min)	3400
Screw speed(r/min)	3370
Separation factor	2907
Feed flow rate(m^3/h)	5
Differential speed(r/min)	30
Operating pressure(Pa)	101325

Table 4. Material physical properties parameters

Physical Property Parameters	Value
Water volume fraction(%)	0.25
Condensate density(kg/m^3)	780
Condensate viscosity(Pa·s)	0.0009
Floc volume fraction(%)	0.25
Floc density(kg/m^3)	860
Floc viscosity (Pa·s)	0.0042

Fig.6 shows the static pressure cloud diagram of two-phase (oil-water) separation and the volume fraction cloud diagram of each phase, and Fig.7 shows the three-phase (oil-water floc) separation and the volume fraction cloud diagram of each phase. It can be seen from the static pressure cloud diagram that the pressure of the column section is greater than the pressure of the cone section, and the closer to the wall surface of the column section, the greater the pressure. The smaller the centrifugal pressure in the direction of the slag outlet, this is due to the closer to the sand outlet in the cone section, the more the accumulation of flocs and water phase, the screw conveyor and the cone drum together to produce two-way extrusion pressure, forcing flocs and water phase discharge. The static pressure increases rapidly with the increase of the radius of the liquid ring near the overflow port. The pressure of the outlet section gradually decreases along the axial direction, forming a stable pressure drop gradient, which provides pressure driving for the discharge of each phase after separation, which is beneficial to the discharge of liquid to a certain extent.

In the two-phase separation system, in the two-phase separation system, the oil phase is enriched to the center of the flow channel under the action of centrifugal force, and flows close to the wall surface of the spiral core tube ; the water phase density is large, and it is driven by centrifugal force to settle to the inner wall of the drum. In the cone region, due to the stable distribution of water phase, the water phase is mainly occupied near the wall, and the central flow channel is occupied by a small amount of spilled oil phase. The volume fraction of oil phase at the slag outlet is very low, and most of the oil phase overflow outlet is pure oil phase. The overall flow field meets the requirements of two-phase separation, and the separation effect is good.

In the three-phase separation system, the oil phase density is the smallest, which is close to the wall of the spiral core tube ; the floc density is between the oil and water phases and is distributed in the middle layer. The water phase density is the largest, settling to the inner wall of the drum. There is an oil guide hole on the spiral blade of the column section. From the oil phase volume fraction cloud map, it can be seen that the oil guide hole has a guiding auxiliary effect on the oil phase overflow to the oil outlet, which can avoid the accumulation of oil phase. It can be seen from the volume fraction cloud diagram of the flocs that as the flocs are transported to the cone section by the screw conveyor, the flocs in the cone section are continuously enriched, and the effective separation of the flocs and the oil phase is realized, and the separation effect is good. It can be seen from the water phase volume fraction cloud diagram that the water phase distribution is relatively stable, close to the inner wall of the drum, and the separation process is completed under the propulsion of the screw conveyor. The volume fraction of the water phase near the pusher is low, which is complementary to the distribution of the floc phase and the oil phase, reflecting the stratified competition relationship of the three phases in the separation process. The floc density is between the water phase and the oil phase, and the stability is relatively low, so it is enriched and occupies a large proportion in the cone section. The water phase density is the highest, the distribution is relatively stable, and the flow is close to the inner wall of the drum. The oil phase is a light phase. After partially overflowing the oil baffle, it is enriched to the central area of the spiral core tube under the action of centrifugal force. The three-phase stratification is obvious, which verifies that the separation factor of the horizontal screw centrifuge designed in this paper meets the requirements of separating three phases.

In summary, through the simulation of multiphase flow separation, it is clear that the two-phase horizontal screw centrifuge can realize the three-phase separation of oil-water flocs.

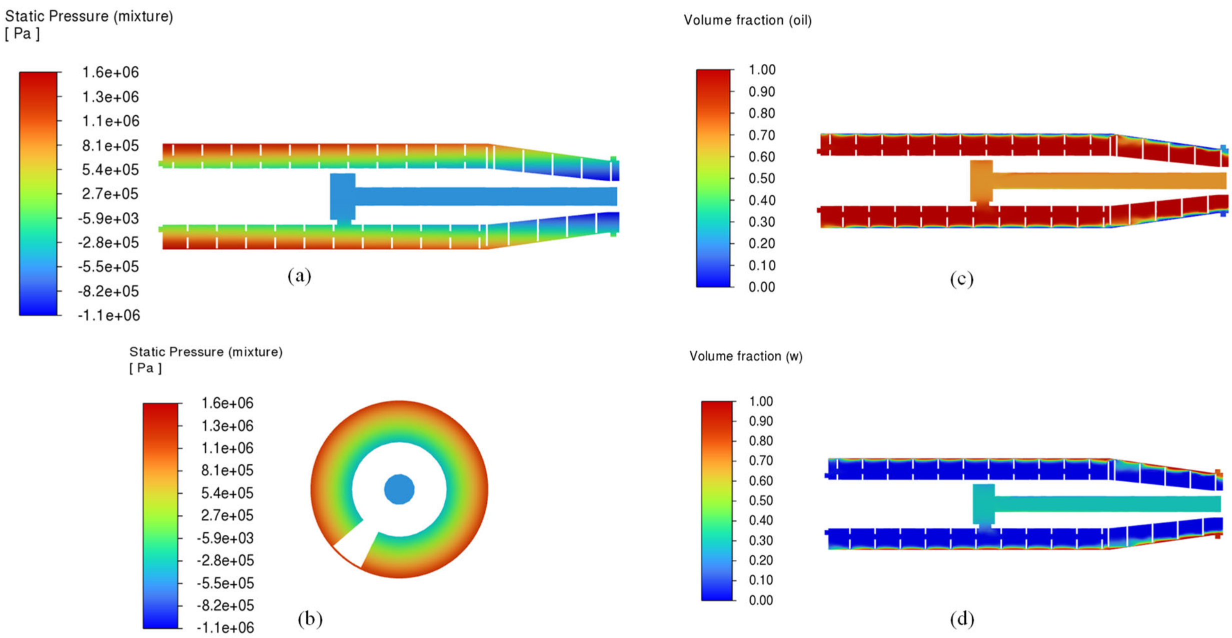


Figure 6. Axial(a) and radial(b) static pressure contours and oil volume fraction(c) and water volume fraction(d) contours.

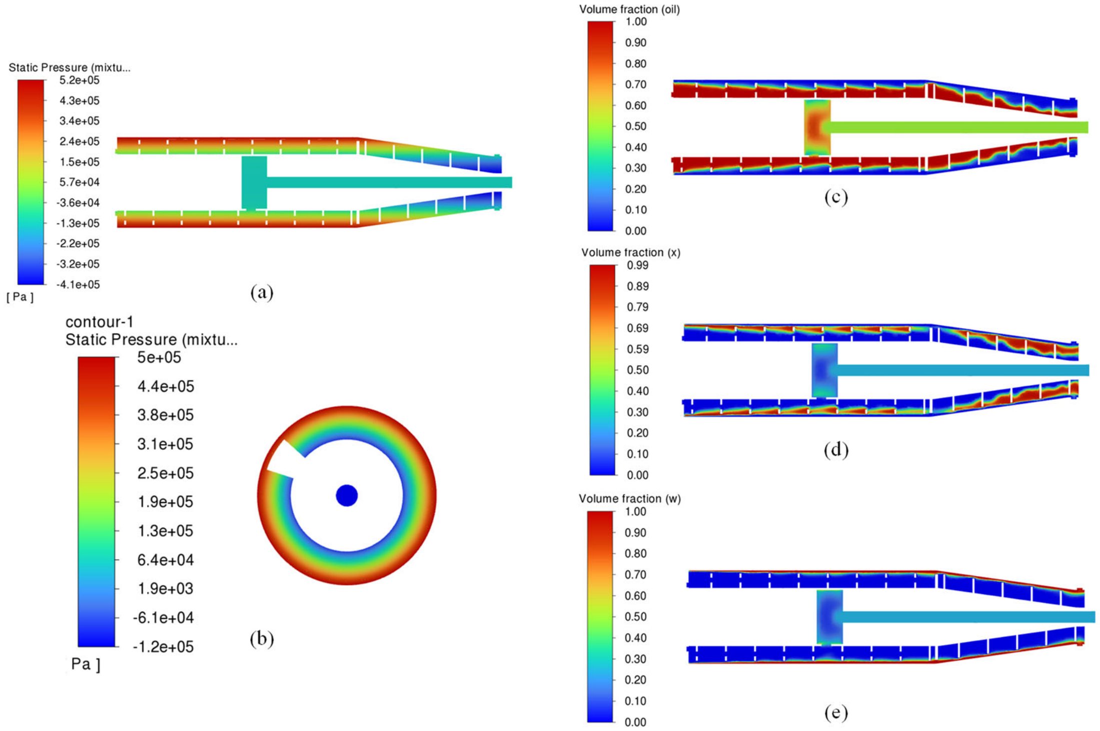


Figure 7. Axial(a) and radial(b) static pressure contours and oil volume fraction(c) and floc volume fraction(d) and water volume fraction(e) contours

5. Conclusion

(1) Aiming at the floccules in condensate oil, a separation scheme of condensate oil floccules is designed to separate condensate oil, water and floccules to meet industrial requirements.

(2) By investigating different separation schemes, comparing the adaptability and economy of each separation method, the scheme is optimized, and the horizontal screw centrifuge is finally determined to be used for separation.

(3) The condensate oil separation scheme is designed, the key parameters of the horizontal screw centrifuge are determined, and the three-dimensional model of the main components is established.

(4) The feasibility of the centrifugal method was verified by principle experiments, including precipitation test, filtration experiment and centrifugation experiment. Through the finite element simulation, the feasibility of the separation of the two-phase horizontal screw centrifuge is verified, and the feasibility of the separation scheme is determined.

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