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# Experimental research on enhanced the microfine oil droplets separation using hydrocyclone coupled with fiber coalescence

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ABSTRACT

The limitations of swirl separation in removing microfine oil droplets in water have driven the development of hydrocyclone technology coupled with multiphase or multifield techniques. To enhance microfine oil droplets separation, a novel hydrocyclone separation coupled with fiber coalescence (HCCFC) was designed. The interaction between fiber balls and oil droplets inside the hydrocyclone, including droplet coalescence and breakage, was investigated. The influence of different operating parameters on separation efficiency was discussed. The results showed that fiber balls promoted oil droplet coalescence when the inlet droplet size ($D_{43}$) was below 22.37 μm but caused droplet breakage above this threshold. The coalescence performance of HCCFC improved with increasing inlet oil content but declined beyond 450 mg·L$^{-1}$. Separation experiments confirmed that HCCFC outperformed conventional hydrocyclone, with separation efficiency increasing by 2.9% to 20.0%. As the fiber ball content and inlet flow rate increased, the separation efficiency showed a trend of first increasing and then decreasing. Additionally, HCCFC's separation efficiency varied with inlet oil droplet size distribution, showing the most significant enhancement when $D_{43}$ was 22.37 μm, where separation efficiency increased by 14.4%. These findings offer insights into the development and application of multiphase coupled with hydrocyclone technology.

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## 1. Introduction

Oily wastewater is a kind of pollutant that poses a threat to the environment and human health [1,2], and its sources are wide. Oil exploitation, iron and steel smelting, metal processing, crude oil production, food processing and other production processes may produce a large amount of oily wastewater [3,4]. There are many types of oily wastewater, which can be classified into four categories based on the forms of oil presence in water: floating oil (droplet size greater than 100 μm), dispersed oil (droplet size between 20 and 100 μm), emulsified oil (droplet size between 0.1 and 20 μm), and dissolved oil (droplet size less than 0.1 μm). Over the years, various oil–water separation technologies have been widely developed and applied in pursuit of efficient, low-carbon, and sustainable treatment methods. Currently, common methods for oil–water separation include gravity separation [5–7], flotation [8,9], membrane separation [10,11], and chemical demulsification [12,13]. Among these methods, hydrocyclone separation equipment has attracted considerable attention due to its advantages of compact structure, simple operation, strong processing capability and high separation efficiency [14], and has been widely used in the petroleum, chemical, and environmental protection fields. It is worth noting that when using hydrocyclone to treat oily wastewater, the floating oil can usually be separated effectively, but the separation effect is not good for the oil droplets with small particle size, such as dispersed oil and emulsified oil. Therefore, how to further improve the separation efficiency of the hydrocyclone for dispersed oil has become a crucial problem.

Hydrocyclone equipment utilizes centrifugal force generated by liquid rotation to achieve the separation of different substances. The separation performance of hydrocyclone is influenced by various factors. In recent years, the development trend of hydrocyclone has shifted from the traditional structure improvement [15–17] and process optimization [18–21] to the integrating novel technologies and methods, including the coupling of hydrocyclone

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with multiphase or multifield [22,23]. Liu *et al.* [24] designed a magnetic hydrocyclone under the coupling action of centrifugal force field and magnetic field, verifying that the magnetic field coupled swirling field could significantly improve oil–water separation efficiency. Gong *et al.* [25] first used an electric field to coalesce oil droplets, then combined the hydrocyclone to rapidly separate the coalesced oil droplets, which significantly improved the separation efficiency of microfine oil droplets. Huo *et al.* [26] analyzed the oil–water separation process under the influence of voltage and demonstrated that the electric field could enlarge the size of oil droplets in the flow field, which was conducive to improving the oil–water separation efficiency. These studies indicate that microfine oil droplets that are difficult to remove can be condensed into large oil droplets that are easy to separate through multi-physical coupling, thus effectively improving the separation performance of hydrocyclone. However, the method of enhancing separation by adding magnetic field and electric field in hydrocyclone has some limitations, such as large equipment investment, high energy consumption and certain safety risks, which are bottlenecks in practical applications. In addition, it is an effective method to strengthen separation by using bubbles. Raesi and Maddahian [27] combined bubbles with hydrocyclones and evaluated the impact of air-injected deoiling hydrocyclones from the perspectives of three-phase flow fields, oil droplet distribution, and separation efficiency. In fact, there are some problems in this method, such as bubble size fluctuation and bubble disappearance during separation. In contrast, adding solid phase media such as fiber balls to the hydrocyclone can effectively solve these problems. Without adding additional physical fields, the fiber medium interacts and couple with the oil droplets by centrifugal force in the hydrocyclone. Simultaneously, fiber materials are cheap and have large specific surface area and high surface roughness. This surface property allows the fiber to provide more contact area and increase the chance of contact with the oil molecules, thus facilitating the oil droplet coalescence process.

Currently, existing research mainly focuses on multifield coupling methods such as magnetic field-swirling flow field, electric field-hydrocyclone separation, and air flotation-hydrocyclone separation to improve the separation efficiency of hydrocyclone. Nevertheless, there are some unavoidable problems in these methods. In order to solve the problems of existing integrating separation technologies, a new idea of coupling fiber coalescence technology and swirl separation technology to strengthen oil–water separation is proposed in this study. Fiber coalescence utilizes the difference in affinity between fiber materials and oil–water phases, whereby the oil phase with highly affinity is captured by the fiber material, and as droplets gradually coalesce and increase, they begin to detach after reaching a certain oil droplet size. By adding fiber media to hydrocyclone, these media will effectively capture microfine oil droplets and make them coalesce into large oil droplets, so as to realize effective separation of microfine oil droplets in swirl field. The study of fiber coalescence has been widely reported. In the early stage, the surface modification of fiber, operating conditions, and optimization of fiber bed structure have been studied [28–30]. With the development of high-speed photography technology, in order to deeply understand the mechanism of droplet movement during fiber coalescence, the research focus has shifted from macroscopic process to microscopic process. Recent studies have focused on the morphology evolution of droplet coalescence [31], the growth mechanism of liquid bridges [32], and the dynamic characteristic of droplets on fibers [33]. To sum up, the fiber coalescence technology has a certain research basis. Based on the principle of fiber coalescence, the combination of fiber coalescence technology and swirl separation technology, so as to achieve efficient green separation of small oil droplets is feasible. Compared with the above integrating method, the method has the advantages of high efficiency, low energy consumption, low cost, wide application range and no secondary pollution.

In this work, focusing on the field of oil–water separation, a novel method of hydrocyclone coupled with fiber coalescence (HCCFC) was proposed to enhance the separation of microfine oil droplets in water. The coalescence and breakage performance of oil droplets in HCCFC were analyzed in detail through experimental studies. Simultaneously, the separation effect of HCCFC on microfine oil droplets was evaluated comprehensively. This study provides a new idea for improving the hydrocyclone separation technology in the field of water treatment, and lays a foundation for enhancing the industrial application level of hydrocyclone.

## 2. Experimental

### 2.1. Principle of coupled separation

In this study, a hydrocyclone was combined with fiber coalescence to strengthen the separation of microfine oil droplets in water. The principle of hydrocyclone coupled with fiber coalescence to improve oil–water separation is shown in Fig. 1. The process of hydrocyclone coupled with fiber coalescence for enhanced oil–water separation is highly complex, involving multiple disciplines such as fluid mechanics, particle kinematics, and physical chemistry. During the coupling process of fiber balls with the swirling flow field, collisions occur between the fiber balls and the oil droplets. After colliding with the fiber balls, the oil droplets adhere to the surface or interior of the fiber balls. Subsequent oil droplets continuously collide and coalesce with the oil droplets already attached to the fiber balls, forming larger on the fiber ball surface that are easier to separate. These larger droplets then move upward and exit through the overflow outlet, while the water phase moves downward and exits through the underflow outlet, thereby improving separation efficiency, as show in Fig. 1(a). Collision is a key step in the interaction between fiber balls and oil droplets, while the formation of stable larger oil droplets through coalescence are crucial factors in improving oil–water separation efficiency. A sufficiently high collision probability can effectively enhance the separation of microfine oil droplets. The turbulence characteristics in the hydrocyclone will significantly affect the collision probability between the fiber balls and the oil droplets, and then affect the oil–water separation efficiency.

In a hydrocyclone, the movement of oil droplets is mainly influenced by radial and axial forces. Radial forces include centrifugal force, pressure gradient force, Stokes resistance, and Magnus force, while axial forces include gravity force, buoyancy force, and Stokes resistance. Under the influence of centrifugal force and buoyancy force, oil droplets will move in the direction of the center and top overflow. Smaller oil droplets, due to weaker centrifugal force and buoyancy force, usually move along with the water phase towards the wall and downward to the underflow. To improve the oil–water separation effect, fiber balls are introduced into the hydrocyclone separation system. The fiber balls move radially from the outside in and axially from the bottom up, colliding with smaller oil droplets moving outward and downward, forming reverse interception collisions. This causes oil droplets to attach to the fiber balls, forming fiber ball–oil droplet complexes. These complexes have higher viscosity, which promotes the coalescence of oil droplets upon collision with other oil droplets to form a stable and easily separable large oil droplet, as show in Fig. 1(b) and (c). Additionally, as fiber balls push oil droplets inward and upward, it also promotes mutual collision and coalescence among the oil droplets. In HCCFC, oil droplets are “carried,” “pushed,” and

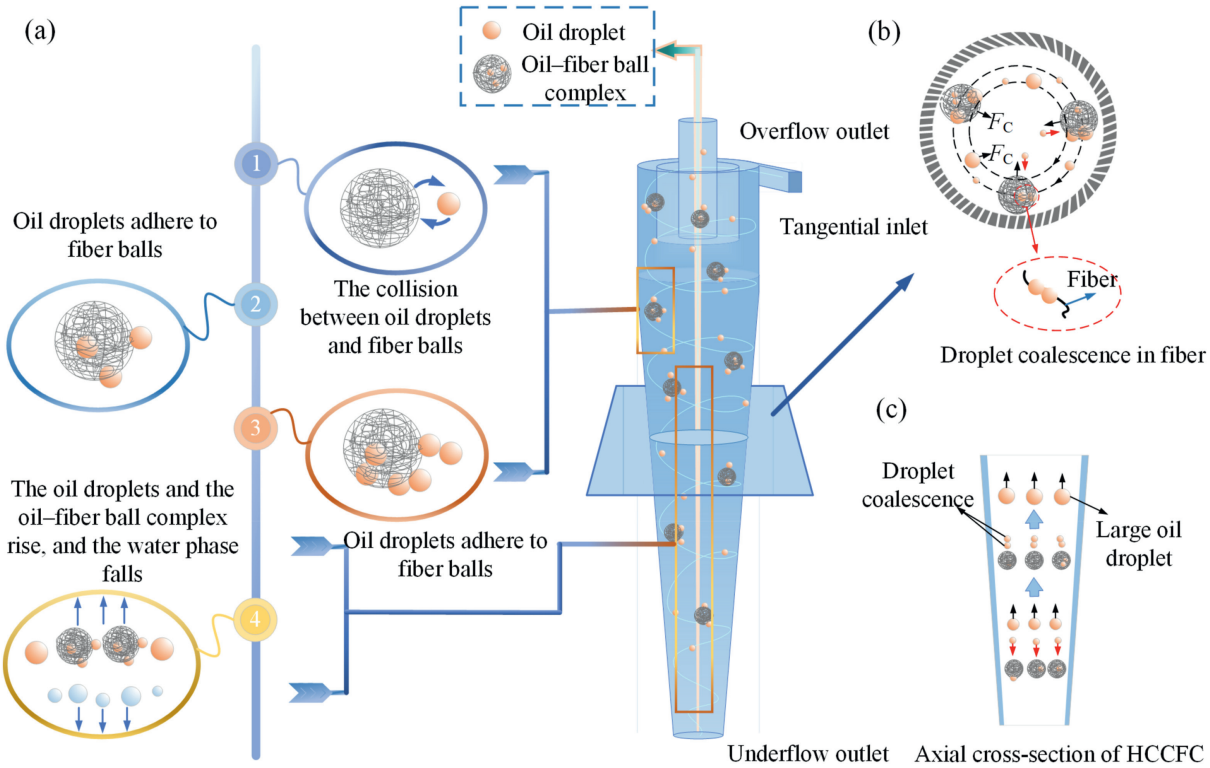
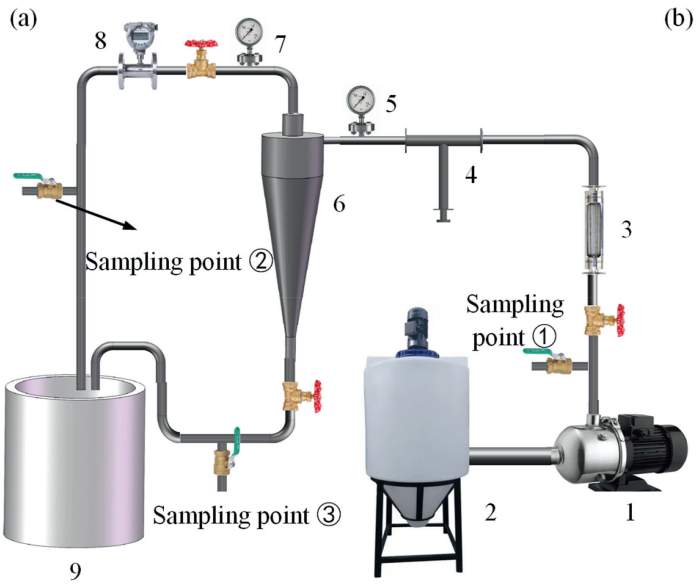



**Fig. 1.** Schematic diagrams of oil–water separation strengthened by hydrocyclone coupled with fiber coalescence.

"coalesced" by the fiber balls, which effectively enhances the difference in the centrifugal force of the oil and water and the contact force on the oil droplets, thereby facilitating the further separation of smaller oil droplets.

### 2.2. Experimental equipment

Fig. 2(a) shows the structural diagram of HCCFC system for enhanced oil–water separation. This system mainly consisted of hydrocyclone, fiber ball feeder, flow meter, pressure gauge, centrifugal pump, and oily wastewater storage tank. In this study, oil and water were first mixed in the required proportions, and then the oil–water mixture was cut into emulsion by high-speed shear (JRJ300-SH, HUXI, China). The prepared emulsion was diluted in the oily wastewater storage tank. Finally, the diluted emulsion was pumped into the hydrocyclone for separation experiments using a centrifugal pump (MHI406-1/10E/3-380-50-2/GB3, Wilo, Germany). In the experiments on enhancing oil–water separation using HCCFC, once the flow field in the hydrocyclone was stable, fiber balls were pushed into the hydrocyclone through the fiber ball feeder to improve the separation efficiency of microfine oil droplets. Samples were collected sequentially from the hydrocyclone inlet, oil




(b)

| | |
|---|---|
| $D$/mm | 35 |
| $a$/mm | 8 |
| $b$/mm | 6.2 |
| $L$/mm | 45 |
| $H$/mm | 177 |
| $S$/mm | 21 |
| $d_0$/mm | 12 |
| $d_u$/mm | 8 |

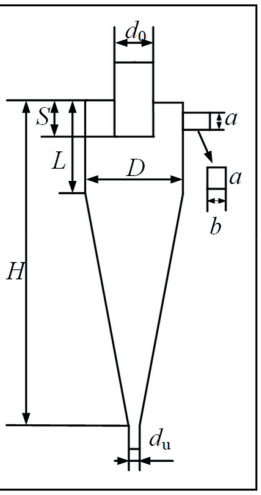



**Fig. 2.** (a) Schematic diagram of the experimental device: 1-centrifugal pump, 2, 9-oily wastewater storage tank, 3-float flowmeter, 4-fiber ball feeder, 5, 7-pressure gauge, 6-hydrocyclone, 8-turbine flowmeter. (b) The structural dimensions of the hydrocyclone.

**Table 1**
Physical parameters of experimental materials.

| Materials | Density/kg·m$^{-3}$ | Kinematic viscosity/mm$^2$·s$^{-1}$ |
|---|---|---|
| Water | 1000 | 1 |
| Oil droplet | 820 | 7 |
| Fiber ball | 360 | / |

outlet, and water outlet. The oil droplet size distribution and oil content in the samples were detected using a laser particle size analyzer (BT-9300ST, Bettersize, China) and an ultraviolet spectrophotometer (UV-1800, Shimadzu, Japan), respectively. Additionally, a hydrocyclone with a diameter of 35 mm was used in this study, and Fig. 2(b) shows the structural dimensions of the hydrocyclone. After each experiment, the remaining liquid in the oily wastewater storage tank was drained to avoid interference with subsequent experimental results. Each set of experiments was repeated three times, and the data were presented as the average value.

### 2.3. Experimental parameters and calculation

In this study, water was used as the continuous phase, while oil droplets and fiber balls acted as the dispersed phases. The fiber balls were made of polypropylene fibers and the diameter of the fiber balls is 2 mm. In addition, the oil used in the experiment was white oil, and its specific parameters are detailed in Table 1. The experimental variables included the inlet oil content, inlet oil droplet size, inlet flow rate, and fiber ball content. The range of inlet oil content was from 210 to 1000 mg·L$^{-1}$, the range of inlet flow rate was from 14 to 22 L·min$^{-1}$, and the range of fiber ball content was from 75 to 200 mg·L$^{-1}$. Additionally, the study focused on the oil–water separation under different volume average diameters of inlet oil droplet was analyzed in detail, and the characteristics of the oil droplet size distribution are provided in Table 2. It is worth noting that since the prepared oil droplet particle size distribution cannot be accurately replicated, the calculated average value is shown in Table 2. $D_{10}$, $D_{50}$, and $D_{90}$ represents the particle size corresponding to a sample when the cumulative particle size distribution percentage reaches 10%, 50%, 90%, respectively. $D_{43}$, the volume average diameter of oil droplet, represents the ratio of the sum of the volumes of all particles to the number of particles in the system. In this study, the volume average particle size reflects the average value of the total volume of oil droplets, providing a more intuitive reflection of volume changes during the oil droplets coalescence process. Since coalescence is essentially a cumulative increase in volume, $D_{43}$ more accurately describes this phenomenon. Therefore, $D_{43}$ was chosen to characterize the coalescence performance of oil droplets. $D_{43}$ is calculated by the following Eq. (1).

$$D_{43} = \frac{\sum_{i=1}^{k} n_i D_i^4}{\sum_{i=1}^{k} n_i D_i^3} \tag{1}$$

where $D_i$ represents the diameter of the $i$-th particle, and $n_i$ represents the number of such particles.

**Table 2**
Size distribution grade of inlet oil droplets.

| Size distribution grade | Characteristic value of inlet oil droplet size distribution/μm | | | |
|---|---|---|---|---|
| | $D_{10}$ | $D_{50}$ | $D_{90}$ | $D_{43}$ |
| 1 | 2.34 | 18.53 | 33.54 | 18.63 |
| 2 | 2.28 | 21.39 | 41.83 | 22.37 |
| 3 | 2.57 | 22.75 | 41.63 | 23.04 |
| 4 | 2.49 | 24.40 | 47.45 | 25.34 |

Separation efficiency $E$, an important metric for evaluating oil–water separation performance, is defined by the following Eq. (2).

$$E = \left(1 - \frac{C_u}{C_{in}}\right) \times 100\% \tag{2}$$

where, $C_u$ represents the oil concentration at the underflow outlet, and $C_{in}$ represents the inlet oil concentration.

To ensure the reproducibility of experiments, the following measures were implemented in this study: (1) Experimental conditions were strictly controlled. For instance, when studying the effect of inlet flow rate on separation efficiency, key parameters such as oil–water mixing ratio, fiber ball content, and inlet oil droplet size were meticulously maintained consistent across all experiments. (2) All experimental procedures followed standardized operating protocols, and detailed records were maintained for critical steps to facilitate subsequent replication. (3) Experimental equipment was thoroughly calibrated before use. For example, the laser particle size analyzer was securely fixed in position, and sample measurements were conducted immediately after collection to minimize errors. (4) Each set of experiments was repeated three times within a short period. The results showed that the standard deviation of the data was within 10%, demonstrating a reasonable degree of stability.

## 3. Results and Discussion

### 3.1. Analysis of coalescence performance

Coalescence of dispersed oil droplets occurs within the hydrocyclone. Research shows that coalescence enhances oil–water separation performance. Zhang *et al.* [31] investigated the coalescence behavior of droplets in droplet–fiber systems versus droplet-non-fiber systems. The results indicated that the presence of fibers accelerates the coalescence process of droplets. As a uniquely shaped medium, fibers provide specific conditions on surface and structure, which is conducive to droplet coalescence. Simultaneously, fibers inhibit the intensity of the droplet coalescence process, reducing the generation of secondary droplets. This finding suggests that fibers can prevent droplet breakage, thereby promoting increased oil–water separation efficiency. Based on existing research, it can be hypothesized that the presence of fiber balls in a hydrocyclone may enhance the coalescence performance of oil droplets in the swirling flow field. To verify this hypothesis, the coalescence performance of conventional hydrocyclone (CHC) and HCCFC are analyzed in detail in this study. Through the comparison and analysis of the experimental results, the mechanism of fiber in oil–water separation process can be understood more deeply.

The introduction of polypropylene fiber balls in HCCFC aims to enhance the coalescence efficiency within the equipment. Due to the crucial role of the material properties of the fiber balls in coalescence performance, it is particularly necessary to investigate the physical properties of polypropylene fibers. As depicted in Fig. 3(a), the wetting behaviors of water and oil on the surface of polypropylene fibers are shown. Through observation, it is discovered that the contact angle of water on the surface of polypropylene fibers in air reach 109°, while the contact angle of oil in water is 50°. This data reveals that the affinity of polypropylene fibers for the oil phase is significantly higher than that for the water phase, exhibiting stronger lipophilicity and hydrophobicity. Consequently, polypropylene fiber balls can effectively adsorb oil droplets, promote the coalescence of oil droplets on the material surface, and thereby significantly improve the coalescence effect of HCCFC.

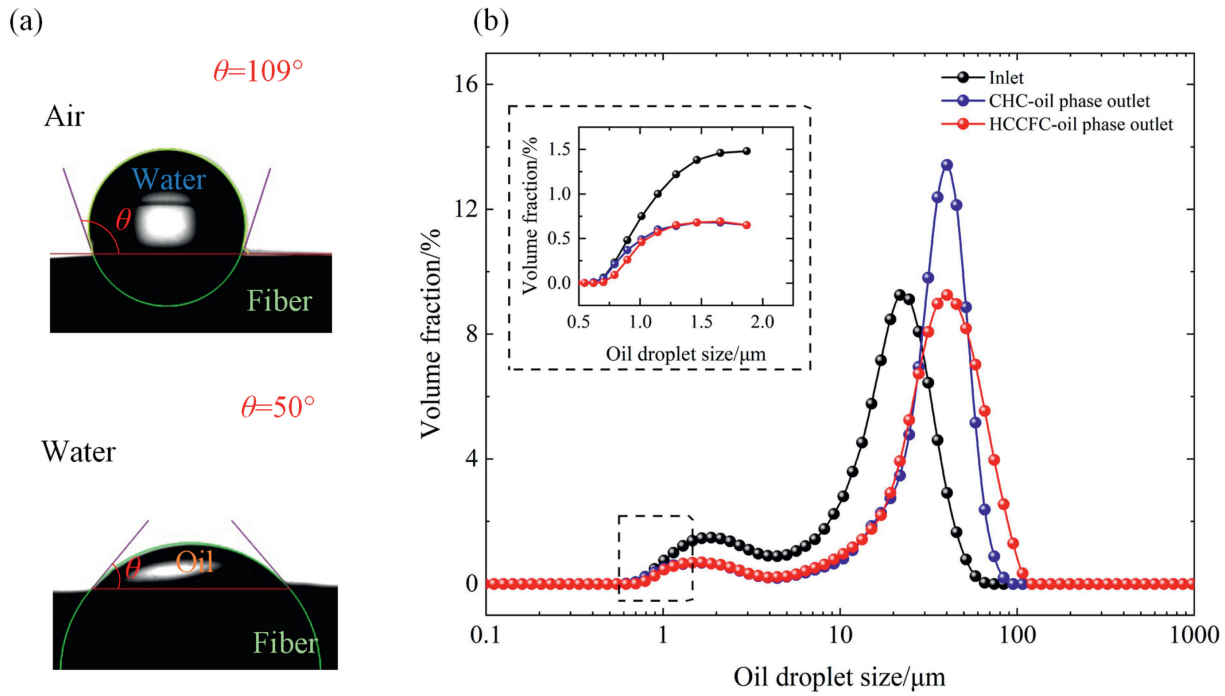



**Fig. 3.** (a) Water and oil wetting behaviors on the surface of fiber. (b) The oil droplet size distributions during coalescence in HCCFC.

To analyze the coalescence performance of CHC and HCCFC, the inlet flow rate is adjusted to 20 L·min$^{-1}$, the inlet oil content is set to 450 mg·L$^{-1}$, and the volume mean diameter of inlet oil droplet is 18.63 μm. In this study, the oil droplet size distribution at the hydrocyclone inlet, the oil phase outlet of CHC, and the oil phase outlet of HCCFC are compared and analyzed. The specific results are shown in Fig. 3(b). By observing the curve in the figure, it can be found that the oil droplet size corresponding to the volume fraction peak of oil droplets at the hydrocyclone inlet is smaller than that corresponding to the volume fraction peak of oil droplets at the oil phase outlet of CHC and the oil phase outlet of HCCFC, indicating the presence of coalescence within the hydrocyclone. Additionally, it can be observed from the figure that the volume fraction of small-sized oil droplets at the oil phase outlet of HCCFC is lower than that at the oil phase outlet of CHC. For example, when the oil droplet size distribution range is 0–2 μm, the volume fraction of oil droplets at the oil phase outlet of CHC is 4.4%, whereas it is 4.1% at the oil phase outlet of HCCFC. Furthermore, the volume fraction of large-sized oil droplets at the oil phase outlet of HCCFC is higher than that at the oil phase outlet of CHC. In the size distribution range of 45–200 μm, the volume fraction of oil droplets at the oil phase outlet of CHC is 24.5%, while it reaches 34.1% at the oil phase outlet of HCCFC, which is 9.6% higher than that at CHC. These results indicate that adding fiber balls to the hydrocyclone can effectively enhance its coalescence performance under certain conditions. This effect is primarily attributed to the presence of fiber balls, which not only provide a medium for oil droplet coalescence but also prevent droplet breakage during collisions and coalescence due to the structural support offered by the fibers.

To further verify this conclusion, the coalescence performance of CHC and HCCFC under different inlet oil contents are analyzed in this study. Specifically, the volume average diameter of oil droplets at the oil phase outlets of CHC and HCCFC under different inlet oil contents (210, 420, 450, 750, and 1000 mg·L$^{-1}$) is compared. The results are shown in Table 3. Notably, although the prepared inlet oil droplet size distribution cannot be precisely replicated, the variations are minimal and can be considered negligible in terms of their impact on coalescence performance. Therefore, the analysis primarily focuses on the effect of inlet oil concentration on coalescence performance. The table indicates that under different imported oil content, the volume average diameter of the oil phase outlet of HCCFC, as well as that of CHC, is larger than the volume average diameter of the inlet oil droplets. In addition, within the range of inlet oil concentrations from 210 to 1000 mg·L$^{-1}$, the volume average diameter of oil droplets at the oil phase outlet of HCCFC is higher than that at the oil phase outlet of CHC. This further confirms that the coalescence performance of HCCFC is superior to that of CHC under certain conditions. Moreover, as the inlet oil contents increases, the volume average diameter of oil droplets at the oil phase outlet of HCCFC first increases and then decreases, indicating that excessive inlet oil content can inhibit the coalescence performance of HCCFC. This phenomenon may be attributed to the significant increase in the number of oil droplets per unit volume as the inlet oil concentration rises. However, the limited contact area of the fibers and altered turbulence characteristics under high concentration conditions may reduce the coalescence efficiency of oil droplets after collisions.

**Table 3**
The volume average diameter (μm) of oil droplets under different inlet oil contents.

| Inlet oil contents/mg·L$^{-1}$ | $D_{43}$ | | |
|---|---|---|---|
| | Inlet | HCCFC | CHC |
| 210 | 18.01 | 20.49 | 19.03 |
| 420 | 18.37 | 31.89 | 26.69 |
| 450 | 18.63 | 38.06 | 34.06 |
| 750 | 18.21 | 37.02 | 29.73 |
| 1000 | 19.93 | 31.95 | 31.91 |

### 3.2. Analysis of breakage performance

Within the hydrocyclone, both coalescence and breakage phenomena occur. While coalescence improves the efficiency of oil–water separation, the presence of breakage reduces the

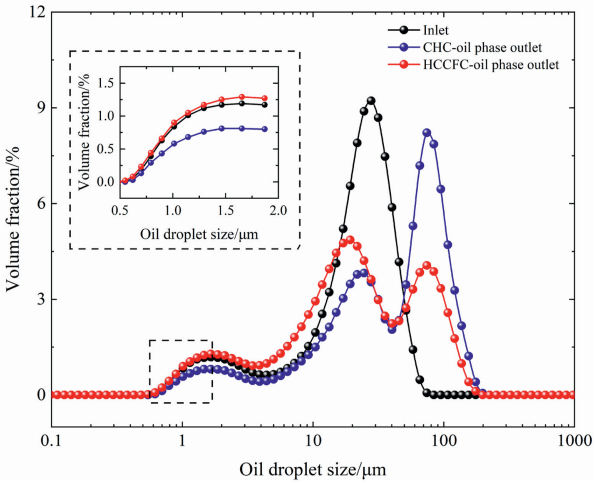



**Fig. 4.** The oil droplet size distributions during breakage in HCCFC.

separation efficiency of the hydrocyclone. Therefore, it is necessary to analyze the breakage phenomenon of oil droplets in hydrocyclone. In this study, the effect of fiber balls on oil droplet breakage within the hydrocyclone is investigated by analyzing the oil droplet size distribution. When the inlet flow rate is 20 L·min$^{-1}$, the inlet oil contents is set at 450 mg·L$^{-1}$, and the volume average diameter of the inlet oil droplets is 23.04 μm, the oil droplet size distributions at the hydrocyclone inlet, the oil phase outlet of CHC, and the oil phase outlet of HCCFC are shown in Fig. 4. Notably, the oil droplet size corresponding to the volume fraction peak of oil droplets at the oil phase outlet of CHC is larger than that at the hydrocyclone inlet. Interestingly, however, the oil droplet size corresponding to the volume fraction peak of oil droplets at the oil phase outlet of HCCFC is smaller than that at the hydrocyclone inlet, indicating a higher presence of small-sized oil droplets at the HCCFC outlet. Furthermore, the figure shows that the volume fraction of small-sized oil droplets (0–2 μm) at the oil phase outlet of HCCFC is significantly higher than at the hydrocyclone inlet and the oil phase outlet of CHC, with volume fractions of 8.4%, 7.8%, and 5.4%, respectively. For oil droplets size larger than 75 μm, the volume fraction at the oil phase outlet of HCCFC is significantly lower than that at the oil phase outlet of CHC, by 14.8%. When the oil droplet size distribution range is 75–300 μm, the volume fractions of oil droplets at the oil phase outlet of HCCFC and CHC are 14.8% and 29.6%, respectively. These results suggest that under specific conditions, the presence of fiber balls within the hydrocyclone can lead to droplet breakage, thereby reducing the coalescence performance of the hydrocyclone and affecting the efficiency of oil–water separation.

Table 4 shows the volume average diameter of oil droplets at the oil phase outlets of HCCFC and CHC under different inlet oil droplet size distributions. As shown in the table, when the volume average diameter of the inlet oil droplets ranges from 18.63 to 22.37 μm, the oil droplets at the oil phase outlet of HCCFC have a larger volume average diameter compared to CHC. As the inlet oil droplet size increases, the volume average diameter of oil droplets at the oil phase outlet of HCCFC also increases. However, when the volume average diameter of the inlet oil droplets ranges from 23.04 to 25.34 μm, the oil droplets at the oil phase outlet of HCCFC have a smaller volume average diameter than those at CHC outlet. This suggests that the fiber balls in the hydrocyclone can cause droplet breakage when the inlet oil droplet size distribution is larger. This may be attributed to the formation of larger oil droplets on the fibers, which are subjected to stronger turbulent shear forces within the fluid, making them more susceptible to breakage. In contrast, smaller oil droplets, supported by surface tension, are relatively more resistant to breakage. Furthermore, the limited effective contact area between larger oil droplets and the fiber ball surface hinders their adhesion or coalescence. Instead, repeated collisions may lead to further fragmentation.

**Table 4**
The volume average diameter of inlet oil droplets under different size distributions.

| Size distributions of inlet oil droplets/μm | $D_{43}$ | |
|---|---|---|
| | HCCFC | CHC |
| 18.63 | 38.06 | 34.06 |
| 22.37 | 50.60 | 48.72 |
| 23.04 | 33.90 | 52.21 |
| 25.34 | 11.82 | 35.68 |

In summary, when the volume average diameter of the inlet oil droplets is less than 22.37 μm, the fiber balls within the hydrocyclone is conducive to promoting the coalescence of oil droplets, and the coalescence performance of HCCFC is better than that of CHC. Additionally, under conditions of smaller inlet oil droplet sizes (with a volume average diameter of 18.63 μm), the coalescence performance of HCCFC gradually improves as the inlet oil contents increases. However, when the inlet oil contents exceed 450 mg·L$^{-1}$, the coalescence performance of HCCFC begins to decline. Nonetheless, it still remains superior to the coalescence performance of CHC.

### 3.3. Analysis of separation performance

#### 3.3.1. Effect of inlet flow rate on separation efficiency

The inlet flow rate of the hydrocyclone is one of the key factors affecting separation performance. Optimizing the inlet flow rate can effectively improve the oil–water separation efficiency of the hydrocyclone. By adjusting the inlet flow rate, the motion state of the liquid phase within the hydrocyclone can be altered, thereby influencing the movement trajectory of oil droplets, and then affecting the separation effect. A higher inlet flow rate increases the centrifugal force acting on the oil droplets, promoting the separation of oil from the water phase and enhancing separation efficiency. However, excessively high inlet flow rates may lead to re-emulsification of the oil droplets, thereby reducing separation efficiency. Therefore, in the design and operation of hydrocyclones, it is crucial to carefully select the appropriate inlet flow rate to achieve optimal separation.

In this study, the effects of different inlet flow rates (14, 16, 18, 20, and 22 L·min$^{-1}$) on the separation performance of CHC and HCCFC are analyzed. The inlet oil content is maintained at a fixed level of 1000 mg·L$^{-1}$, and the volume average diameter of inlet oil droplets is 22.37 μm. During the experiments involving oil–water separation with HCCFC, the fiber ball content is kept at 75 mg·L$^{-1}$. By adjusting the inlet flow rate, the changes in separation performance of HCCFC under different conditions are observed, as shown in Fig. 5. As the inlet flow rate increase, the separation efficiency of CHC gradually increase, reaching a maximum value of 67.2% at an inlet flow rate of 20 L·min$^{-1}$. However, when the inlet flow rate is further increased, the separation efficiency of CHC shows a downward trend, which is consistent with the research results of Lv *et al.* [34]. Interestingly, the effect of adding fiber balls on separation efficiency also changes under different inlet flow conditions. Experimental results show that the separation efficiency of HCCFC is significantly higher than that of CHC without fiber balls. This result is in line with expectations, as fiber balls can provide more surface area for contact, thereby enhancing oil–water separation. However, it is worth noting that this enhancement effect is gradually diminished with increasing inlet flow rate. For example, at inlet flow rates of 14, 18,

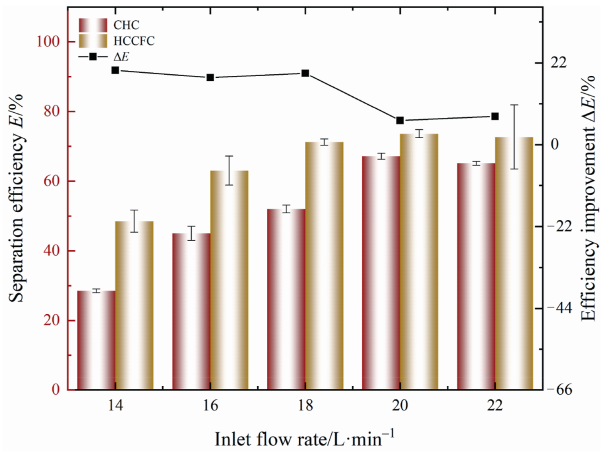



**Fig. 5.** Separation efficiencies at different inlet flow rates.

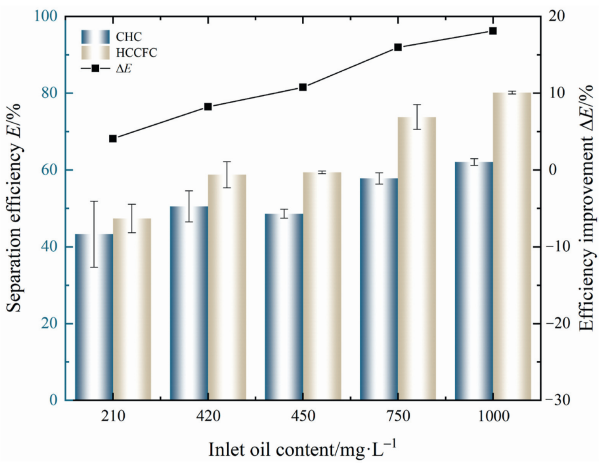



**Fig. 6.** Influences of different inlet oil content on separation efficiency.

and 22 L·min$^{-1}$, the separation efficiency of HCCFC is increased by 20.0%, 19.2%, and 7.6%, respectively, compared with that of CHC. The main reason for this phenomenon is that with the increase in inlet flow rate, the turbulent kinetic energy within the hydrocyclone also increases, leading to higher collision frequency and intensity between droplets and fiber balls, which further increases the probability of droplet breakage, causing emulsification of oil droplets. Additionally, increased turbulence is not conducive to the adhesion of oil droplets to the fiber balls, thus reducing oil–water separation efficiency. Moreover, as seen from the figure, the separation efficiency of HCCFC first increases and then decreases with increasing inlet flow rate. At an inlet flow rate of 20 L·min$^{-1}$, the separation efficiency of HCCFC reach a maximum value of 73.7%.

Overall, within the range of inlet flow rates from 14 to 22 L·min$^{-1}$, the separation efficiency of the hydrocyclone with added fiber balls is higher than that of the conventional hydrocyclone without fiber balls. This indicates that the separation performance of HCCFC is superior to that of CHC. At an inlet flow rate of 20 L·min$^{-1}$, the separation efficiencies of HCCFC and CHC reach 73.7% and 67.2%, respectively, demonstrating the best separation performance.

### 3.3.2. *Effect of inlet oil content on separation efficiency*

To study the effect of different inlet oil contents on the separation performance of CHC and HCCFC, the inlet flow rate is fixed at 20 L·min$^{-1}$, with the volume average diameter of the inlet oil droplets maintain at 18.63 μm, and the fiber ball content set at 75 mg·L$^{-1}$. In the experiment, the separation performance is investigated under different inlet oil content conditions, including 210, 420, 450, 750, and 1000 mg·L$^{-1}$, as show in Fig. 6. It can be clearly observed from the figure that with the increase in inlet oil content, both the separation efficiency of HCCFC and CHC exhibit a gradually increasing trend. At an inlet oil content of 210 mg·L$^{-1}$, the separation efficiency of HCCFC and CHC are at their minimum values, 47.4% and 43.3%, respectively. When the inlet oil content increases to 1000 mg·L$^{-1}$, the separation efficiency of HCCFC and CHC reach their maximum values, 80.2% and 62.1%, respectively. This may be because, at high oil concentrations, the number of oil droplets increases, leading to more frequent interactions among them. Particularly for small oil droplets, collisions and coalescence among the droplets result in the formation of larger droplets, thereby improving the separation efficiency of the oil–water separation system. Moreover, under the same conditions, the separation efficiency of HCCFC is consistently higher than that of CHC. The difference of separation efficiency between HCCFC and CHC also shows an increasing trend with higher inlet oil content. At an inlet oil content of 1000 mg·L$^{-1}$, the separation efficiency of HCCFC is 18.1% higher than that of CHC. This trend can be attributed to the increased inlet oil content, which enhances the probability of oil droplet coalescence on the fiber ball surfaces. More oil droplets coalesce into larger droplets on the fiber balls, thus improving the effectiveness of the oil–water separation process. Additionally, the presence of fiber balls facilitates the adsorption and capture of oil droplets. Particularly at high oil contents, the fiber balls can more effectively capture the oil droplets and prevent them from re-entering the fluid, further enhancing the separation efficiency.

### 3.3.3. *Effect of fiber ball content on separation effect*

Based on the above research results, it can be inferred that adding fiber balls to the hydrocyclone can effectively improve the separation efficiency of oil droplets in the swirling flow field. As an organic nanomaterial, fiber balls play a role in guiding the aggregation of oil droplets in the swirling flow field, thereby forming larger oil droplets. The increase in droplet size helps to improve the oil–water separation efficiency because larger oil droplets are more easily removed by the hydrocyclone. However, the presence of fiber balls may also lead to some negative effects, such as when the fiber ball content is too high, the interaction between the fiber ball and the oil droplet increases, which may reduce the coalescence efficiency and thus affecting the oil–water separation performance. Therefore, it is necessary to analyze the effect of fiber ball content on the hydrocyclone separation efficiency. When studying the impact of fiber ball content on the separation efficiency of the hydrocyclone, the inlet flow rate is adjusted to the optimal treatment rate determined by the experiment, which is 20 L·min$^{-1}$. The inlet oil content is maintained at 1000 mg·L$^{-1}$, with a volume average diameter of inlet oil droplets at 22.37 μm. The separation efficiency changes with fiber ball content are illustrated in Fig. 7. From Fig. 7, it can be observed that as the fiber ball content increases, the oil–water separation efficiency first increases and then decreases. When the fiber ball content increases from 75 to 175 mg·L$^{-1}$, the oil–water separation efficiency sharply increases from 73.7% to 78.5%. This is mainly because the significant increase in fiber ball content raises the probability of collisions between fiber balls and oil droplets, thereby increasing the likelihood of droplet coalescence. In contrast, when the fiber ball content increases from 175 to 200 mg·L$^{-1}$, the oil–water separation efficiency decreases from 78.5% to 77.3%. At this point, the excessively high fiber ball content may cause agglomeration among the fiber balls,

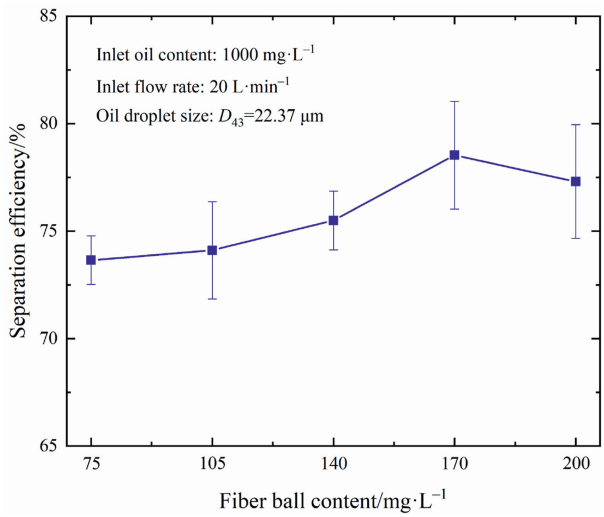



**Fig. 7.** Separation efficiencies under different fiber ball content.

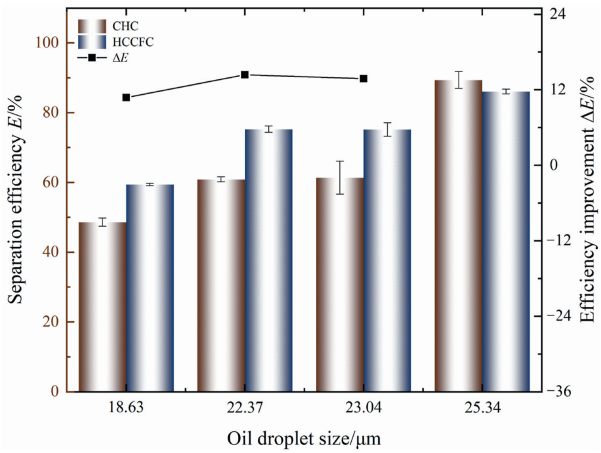



**Fig. 8.** Separation efficiencies under different size distributions of inlet oil droplet.

reducing the oil droplet attachment area. Thus, the oil–water separation efficiency is reduced.

*3.3.4. The separation effect of microfine oil droplets*

During the hydrocyclone separation process, the size of the inlet oil droplets directly affects the separation efficiency of the oil and water phases under centrifugal force. Effective separation of microfine oil droplets is a common challenge faced by all hydrocyclones. To achieve high-efficiency separation of microfine oil droplets, more turbulent kinetic energy is required. However, the probability of microfine oil droplets breaking up in the flow field will increase under high turbulent kinetic energy, adversely affecting the subsequent separation process. Therefore, the purpose of this section is to investigate the separation efficiency of microfine oil droplets using HCCFC, without increasing the turbulent kinetic energy. In this study, four different oil–water mixtures with varying oil droplet size distributions are used, as detail in Table 2. The inlet flow rate is kept constant at 20 L·min$^{-1}$, while the inlet oil content is adjusted within the range of 450 mg·L$^{-1}$, and the fiber ball content is set at 75 mg·L$^{-1}$. The separation efficiency of microfine oil droplets by CHC and HCCFC is compared, as show in Fig. 8. The experimental results show that with the increase in the inlet oil droplet size, the separation efficiency of CHC exhibits an increasing trend. This finding is consistent with the research results of Liu *et al.* [35], which indicate that the larger the inlet oil droplet size, the better the separation. Similarly, when using HCCFC to separate microfine oil droplets, the separation efficiency also increases with the increase in inlet oil droplet size. Specifically, under the condition where the volume average diameter of the inlet oil droplets is 25.34 μm, the separation efficiency of HCCFC and CHC reach their highest values, 86.1% and 89.4%, respectively. Conversely, under the condition where the volume average diameter of the inlet oil droplets is 18.63 μm, the separation efficiency of HCCFC and CHC drop to their lowest values, 59.4% and 48.6%, respectively. This change trend is mainly due to the formation of an oil-in-water system in the hydrocyclone when the inlet oil droplet size is smaller. In this case, the microfine oil droplets are carried out with the water from the low-flow outlet, affecting the separation efficiency. Additionally, the study finds that within the range of 18.63 to 23.04 μm for the volume average diameter of the inlet oil droplets, the separation efficiency of HCCFC is higher than that of CHC. However, as the inlet oil droplet size increases and reaches 25.34 μm, the separation efficiency of HCCFC is lower than that of CHC. This may be because large oil droplets, after adhering to the fiber surface, undergo liquid film instability due to their own gravity and shear force, resulting in fragmentation and the formation of smaller oil droplets. Consequently, these smaller droplets exit through the outlet, reducing the separation efficiency. Furthermore, the difference of separation efficiency between HCCFC and CHC first increases and then decreases. Under the condition where the volume average diameter of the oil droplets is 22.37 μm, HCCFC shows the greatest improvement in separation efficiency, increasing by 14.4%. This indicates that the hydrocyclone coupled with fiber coalescence technology can effectively enhance the separation efficiency of microfine oil droplets.

## 4. Conclusions

In this work, a novel method of oil–water separation was proposed to improve the separation of microfine oil droplets by adding fiber balls to the hydrocyclone. The oil–water separation process of hydrocyclone separator–fiber coalescence coupling was studied based on composite force field. By analyzing the size distribution of oil droplet, the effects of fiber balls on the coalescence and breakage of oil droplets within the hydrocyclone were investigated. Additionally, the effects of various operating parameters, such as inlet flow rate, inlet oil content, fiber ball content, and inlet oil droplet size, on the separation efficiency of HCCFC and CHC were compared. The following conclusions were drawn.

(1) Under conditions of smaller inlet oil droplet sizes, the coalescence performance of HCCFC was superior to that of CHC. Specifically, when the volume average diameter of the inlet oil droplets was 18.63 μm, the volume fraction of small oil droplets (0–2 μm) at the oil phase outlet of HCCFC was 0.3% lower than that of the CHC, while the volume fraction of large oil droplets (45–200 μm) was 9.6% higher than that of the CHC. These results indicated that, under certain conditions, the addition of fiber balls could effectively enhance the coalescence performance of the hydrocyclone. Additionally, excessively high inlet oil content could negatively affect the coalescence performance of HCCFC.

(2) Under certain conditions, the presence of fiber balls within the hydrocyclone could cause the oil droplet breakage, reducing the coalescence performance of the hydrocyclone and thus affecting the efficiency of oil–water separation. With different size distributions of inlet oil droplet, the

volume average diameter of oil droplets at the oil phase outlets of HCCFC showed different trends. As the inlet oil droplet size increased, the volume average diameter at the oil phase outlet of HCCFC first increased and then decreased. This indicated that when the inlet oil droplet size was larger, the fiber balls within the hydrocyclone could impact droplet coalescence, causing the occurrence of droplet breakage.

(3) The separation performance experiments showed that HCCFC exhibited superior separation performance compared to CHC under different operating parameters. The separation efficiency of HCCFC could be improved by 2.9% to 20.0%. The influence of different operating parameters on the separation efficiency of HCCFC was different. The study results indicated that with increasing inlet oil content, the separation efficiency of HCCFC gradually increased. Increasing the fiber ball content and inlet flow rate resulted in an initial increase in separation efficiency, followed by a decrease. Additionally, the separation efficiency of HCCFC was significantly different under different size distributions of inlet oil droplet. Specifically, when the volume average diameter of the inlet oil droplets was 22.37 μm, HCCFC had the most obvious enhancement on the oil droplet separation ability, and the separation efficiency was increased by 14.4%. This further confirmed that HCCFC separation technology could effectively improve the separation efficiency of microfine oil droplets.

## CRediT Authorship Contribution Statement

Lian Zhang: Writing – original draft. Zhaojin Lu: Methodology. Likun Ma: Validation. Zhishan Bai: Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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