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Study on the Separation Performance of a Two Cylindrical Section Hydrocyclone under Various Height Ratios

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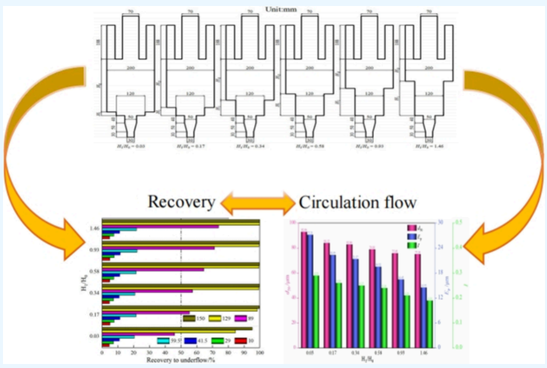
ABSTRACT: Two cylindrical section hydrocyclones can suppress particle misplacement by regulating the circulation flow, but few researchers have investigated the effect of the cylindrical height ratio. In this paper, numerical simulations and physical tests were conducted to investigate the effect of height ratio on the particle motion behavior and separation performance of the two cylindrical section hydrocyclone. According to the numerical simulation results, with increasing height ratio, the separation cut size decreased, the separation accuracy and recovery rate of medium and coarse particles in the underflow increased, the coarse particle misplacement in overflow decreased significantly, and the proportion of medium particle circulation flow gradually increased. According to the test results, the number of misplaced fine particles in underflow could be effectively reduced when H_1/H_0 = 0.30. With increasing height ratio, the number of misplaced coarse particles in the overflow decreased and the classification efficiency of fine particles increased. The maximum separation efficiencies of medium and coarse particles could be obtained at H_1/H_0 values of 0.47 and 0.17, respectively. Therefore, increasing the height ratio could inhibit coarse particle misplacement in overflow and improve the separation performance of two cylindrical section hydrocyclones.



1. INTRODUCTION

Hydrocyclones, which are widely used in various areas, including mineral processing, petrochemicals, environmental protection systems, and biological systems, are used for the separation of nonhomogeneous mixtures via centrifugal sedimentation.[1−4] These devices have the advantages of simple structures, nonmovable parts, and low investment costs, among others. In mineral processing, hydrocyclones are mainly used for classification, sorting, designing, and thickening, in addition to other functions.[5,6] Within hydrocyclones is the separation behavior of particles under the influence of centrifugal force, gravity, buoyancy, drag, etc., which is a highly developed turbulent movement, the internal hydrodynamic properties and particle movement behaviors are extremely complicated.[7−9] Because of their structural limitations, the separation process inevitably involves particle misplacement of overflow and underflow, which is usually characterized by reductions in the recovery yield and quality of the target products. Therefore, alleviating particle misplacement has become a critical issue that is limiting improvements in hydrocyclone separation performance.[10,11]

To improve the separation accuracy of hydrocyclones, many scholars have carried out numerous studies on their operating and structural parameters.[12−14] Ji et al.[15] indicated that a laminar spiral inlet structure could be useful for reducing separation energy consumption, reducing secondary and short-circuit flows, with more significant improvement in classification under high-concentration and low-density feed conditions. E et al.[16] designed a hydrocyclone with a tapered inlet structure, which could reduce the particle mismatch, stabilize the air core, and improve the symmetry of the flow field within hydrocyclone. Pathak et al.[17] reported that an expanding spigot structure could effectively alleviate the phenomenon of roped discharging under the condition of coarse-grained and high-concentration feeding, improving the hydrocyclone separation efficiency. Jiang et al.[18] suggested that an arc-shaped vortex finder has a guiding effect on fluids, which contributes to reductions in the short-circuit flow and circulation flow, reductions in the pressure drop outside the vortex finder, and reductions in the overflow fineness. Gonçalves et al.[19] researched that an appropriate increase in the length of the vortex finder would contribute to the reduction of turbulent disturbances in the separation process, reduce the particle recoveries in the overflow, and improve the separation accuracy of the hydrocyclone. Considering the particle density effect, Ghodrat et al.[20] observed that a convex

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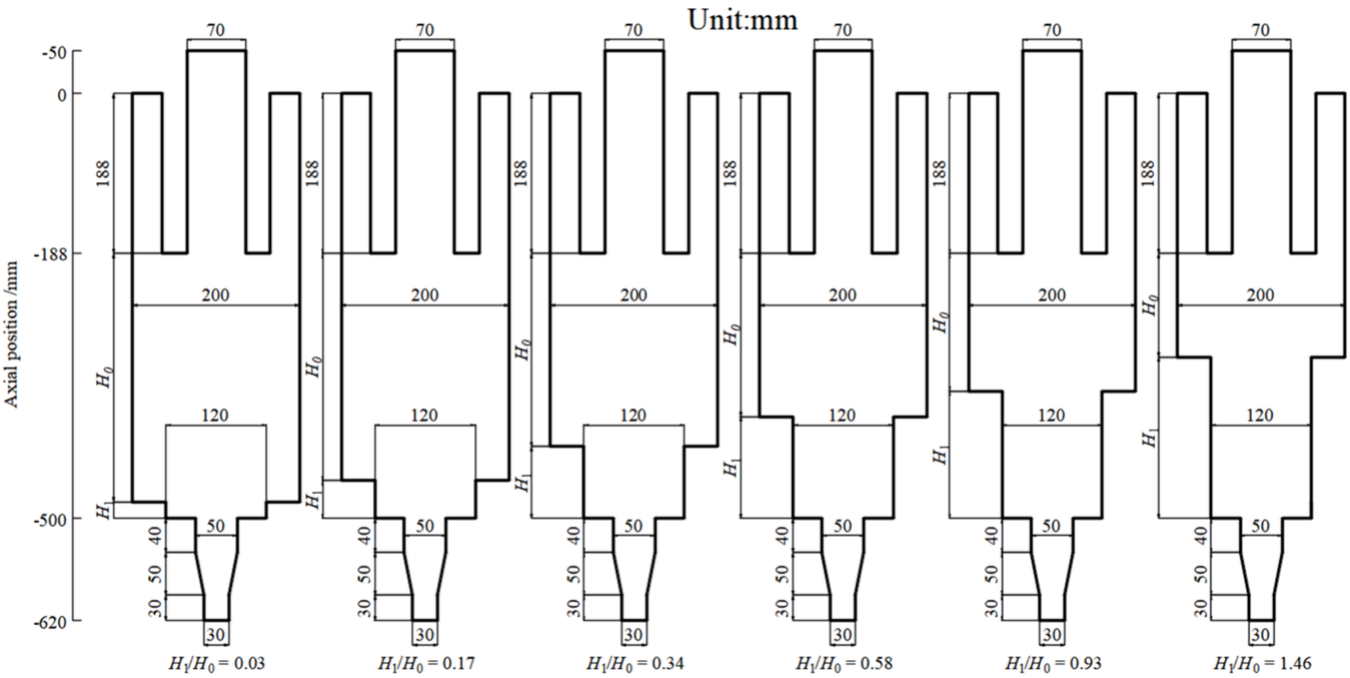

Figure 1. Two cylindrical section hydrocyclones with different height ratios

cone structure contributes to the loosening of the flow field at the bottom of hydrocyclone, the weakening of the flow pressure gradient around the spigot, a reduction in the resistance of light and coarse particles passing through a density layer to reach the external swirling flow, and a reduction in the number of misplaced particles in the overflow. Dou et al.[21] showed that adding flush water could facilitate the entrainment of fine particles in the external swirling flow to participate in the separation process again and reduce the recovery of fine particles of coal sludge with high ash contents in the underflow. The above study aims at the conventional cylindrical-conical hydrocyclone, although the misplacement of fine particles in the underflow can be reduced by optimizing the operating and structural parameters but the reduction is limited due to the inherent defects in its structure.

Flat-bottomed hydrocyclones, which are usually implemented in closed-circuit grinding and classification systems in mineral processing, have the advantages of low concentration of underflow, low allocation of fine particles, and little plugging; however, coarse particle misplacement in overflow can occur.[22] Lu et al.[23] combined numerical simulations and experiments to investigate the flow field pattern inside a flat-bottomed hydrocyclone, and the results showed that increasing the cylindrical height could increase the effective centrifugal settlement space, prolong the particle residence time, reduce the separation pressure drop, and improve the hydrocyclone treatment capacity. Jiang et al.[24,25] investigated the separation performance of a flat-bottomed hydrocyclone with a W-type spigot, and simulation and experimental results revealed that under the guiding effect of a flat-bottomed profile and W structure, fine particles were returned to the internal swirling flow to achieve secondary separation. In addition, the content of particles with sizes of less than 74 μm in the underflow could be decreased by 1.46% according to their industrial experiment. Our team's previous research suggests that a flat-bottomed structure contributes to the suppression of the bypass effect and the reduction in the mismatch of fine particles in underflows; moreover, coarse particles misplacement in overflow can be alleviated by optimizing the bottom wall to regulate the circulation flow of particles. Accordingly, a two cylindrical section hydrocyclone is proposed in terms of regulating the particle circulation flow, and further demonstrates that its separation effect is superior to flat-bottomed hydrocyclones.[26,27] Hence, exploring the effect of structural parameters on the separation performance of the two cylindrical section hydrocyclones based on the current work and carrying out structural optimization to further improve its separation performance are the priority of the current work.

With the development of science and technology, scholars have introduced many advanced experimental methods, such as laser Doppler velocimetry (LDV),[28] volumetric three-component velocimetry (V3V),[29] and electrical resistance tomography (ERT),[30] which are applied to the optimization and design of hydrocyclones to visually represent the internal vortex and particle motion characteristics; however, these methods are difficult to apply to a broad range of fields due to their high equipment cost, poor reducibility, and complicated testing characteristics. Nevertheless, computational fluid dynamics (CFD) is a method that is rising in popularity and can effectively solve these problems.[31,32] Typically, hydrocyclones exhibit strong rotation and high-speed turbulent motion, and Reynolds Stress Model (RSM) and Large Eddy Simulation Model (LES) are typically used to simulate the turbulent behaviors of hydrocyclones. The Volume of Fluid model (VOF), Mixture model, and Two-Fluid Model (TFM) are used to simulate the separation processes of hydrocyclones. The Discrete Element Method (DEM) and Multiphase Particle in Cell (MPPIC) are coupled to further describe the separation characteristics of hydrocyclones under specific conditions.[33−36] Padhi et al.[37] introduced the interaction coefficients and obtained the Algebraic Slip Mixture model (ASM) by modifying the shear lift, settlement resistance, and viscosity coefficients of the mixture model and simulated and verified the classification and separation performance of

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multicomponent particles of silica and magnetite powders. Hou et al.[38] utilized the RSM−TFM model to study the effects of the drag coefficient, wall roughness, and friction stacking limitation on the separation performance of flat-bottomed hydrocyclones during the simulation and obtained a reasonable range of values for the above parameters. Yu et al.[39] showed by simulation that the VOF−DEM model can accurately represent the gas−liquid interface of particle flow and effectively describe the spatial formation process of the air core and the spiral trajectory of particles. Razmi et al.[40] determined the flow field and particle motion characteristics with the LES−MPPIC model, introduced OpenFOAM to solve the mass and momentum equations, and investigated the effects of operating and structural parameters on the separation performance of industrial Sarcheshmeh copper compounds in detail to guide the production process.

The two cylindrical section hydrocyclones can suppress the phenomenon of particle misplacement by regulating the circulation flow to improve the separation accuracy. The height ratio can be considered to determine the distribution of separation space within the hydrocyclone, which directly influences the particle compositions and circulation flow rates and consequently impacts the particle separation effect. In this paper, numerical simulations and physical tests were conducted. First, the particle separation behavior was investigated to explore the circulation flow and particle spatial distribution characteristics with the TFM−RSM coupled model. Second, physical tests were designed to explore the separation performance of the two cylindrical section hydrocyclones and validate the simulation conclusions. The research findings could help to enrich the design theory and provide guidance for the industrial promotion and application of two cylindrical section hydrocyclones.

2. STRUCTURAL DESIGN AND NUMERICAL METHODS

2.1. Design Principle. Previous studies by our group showed that regulating the circulation flow of particles by optimizing hydrocyclone structures could effectively improve the separation effect. The height ratio is the ratio of the lower cylindrical height (H_1) to the upper cylindrical height (H_0), which determines the allocation of separation space within the hydrocyclone and directly affects the circulation flow and separation performance of the particles. In this paper, the other structural parameters of the hydrocyclone were fixed, and the height ratio (H_1/H_0) values were adjusted to 0.03, 0.17, 0.34, 0.58, 0.93, and 1.46 to investigate the influence of the change in the height ratio on the separation performance of the two cylindrical section hydrocyclone. The structure and parameters of the hydrocyclone are listed in Figure 1.

2.2. Simulation Strategy. A hydrocyclone has complicated nonlinear turbulent motion coupled with multiple physical fields. Thus, a reasonable simulation strategy is crucial for ensuring accuracy of the simulation results. In this paper, the simulation was calculated with ANSYS fluent fluid simulation software with model corrections and without the use of custom codes. The simulation process was conducted in two steps. First, the TFM model coupled with the RSM model was utilized to calculate the gas−liquid two-phase fluid motion. Second, based on the stabilized two-phase flow field, discrete-phase particles were injected to calculate the gas−liquid−solid three-phase flow field to investigate the particle's circulation flow characteristics and distribution patterns during the separation process. This simulation method has been widely applied to study the fluid field and separation performance of hydrocyclones. The specific modeling setup can be found in the Supporting Information.

2.3. Numerical Conditions. The inlet boundary condition of the hydrocyclone was set as velocity inlet, and the velocity of each phase was 3m/s. The material used for the physical tests was quartz with a density of 2650 kg/m^3, the mass concentration of the feed was 34.95%, and the volume fraction of the feed was 16.86%. The overall particle distribution was divided into 7 characteristic sizes, as shown in Table 1. The overflow and underflow boundary conditions of the hydrocyclone were set as the pressure outlet with an air return coefficient of 1. The water and air phases were considered no-slip standard walls, and the particle phase was set with a mirror reflectance coefficient of 0.6 toward the wall.

Table 1. Particle Size Distribution and Volume Fraction in the Feed

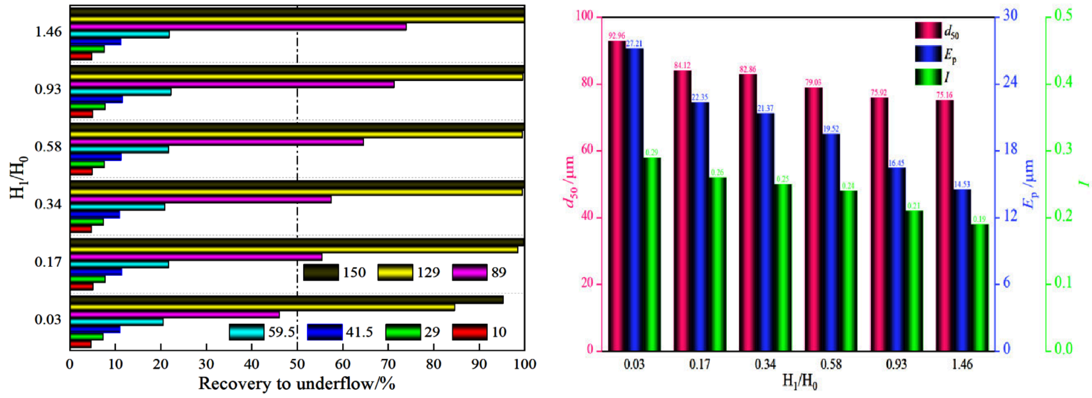
size interval (μm)	mean size (μm)	yield (%)	volume fraction (%)
−20	10	18.98	3.20
20−38	29	23.13	3.90
38−45	41.5	11.86	2.00
45−74	59.5	21.71	3.66
74−104	89	8.90	1.50
104−150	127	8.90	1.50
+150	150	6.52	1.10
total		100	16.86

3. SIMULATION RESULTS AND DISCUSSION

3.1. Separation Performance. Separation efficiency is an important technological index for evaluating hydrocyclone separation process performance and is usually characterized by an efficiency curve, where each point indicates the recovery rates of particles of different sizes in the underflow. Figure 2(a) shows a comparison of the efficiency curves at the different height ratios. As shown in the figure, the height ratio mainly influenced the recovery of medium and coarse particles in the underflow and had a significant regulatory effect on the separation of medium particles. As the height ratio increased, the recovery efficiency of the underflow for medium and coarse particles gradually increased. When H_1/H_0 = 0.03, the structure appeared similar to that of a conventional flat-bottomed hydrocyclone, the regulatory effect of the lower stage on the circulation flow of medium and coarse particles weakened, and the content of coarse particles in the overflow significantly increased compared with that of the other structures, which reflected the feasibility of the two cylindrical structure to alleviate the coarse particles misplacement in overflow.

This paper selects the cut size d_{50}, the possible deviation E_p, and the imperfection I to quantitatively evaluate the efficiency sharpness. The particles of d_{50} have an equal chance of entering underflow and overflow and are described as the particle size corresponding to a recovery value of 50%. E_p and I are employed to evaluate the separation accuracy, which are as small as possible, and their formulas are

$$E_p = \frac{d_{75} - d_{25}}{2} \tag{1}$$



(a) Efficiency diagram (b)Separation performance index

Figure 2. Effects of the height ratio on separation performance

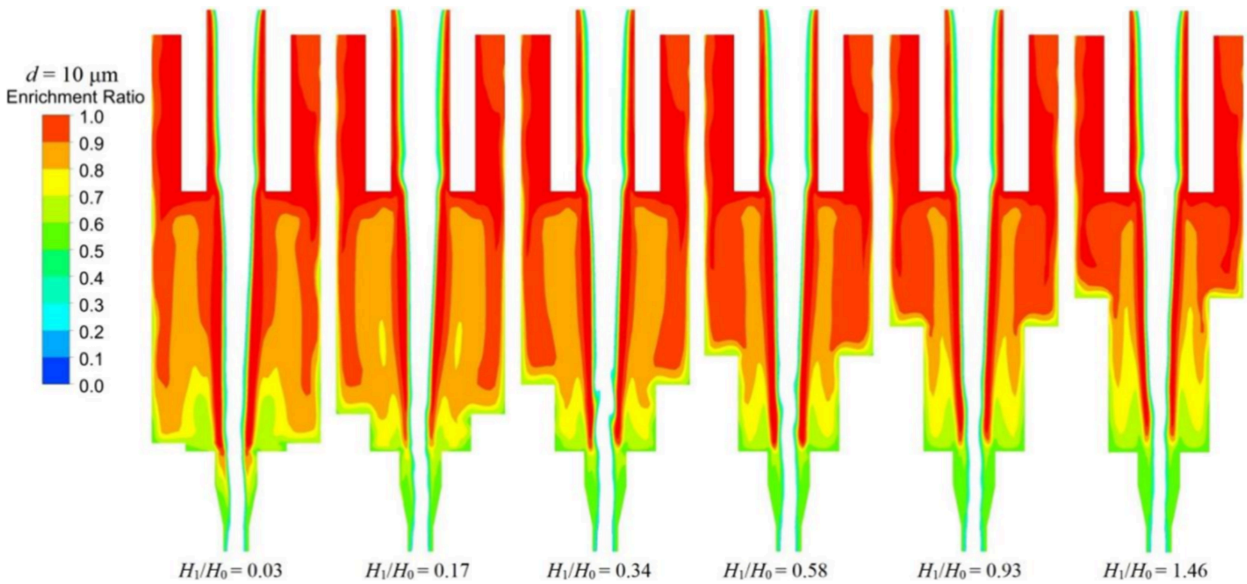


Figure 3. Effect of height ratio on the enrichment ratio of 10 μm particles.

$$I = \frac{d_{75} - d_{25}}{2d_{50}} \quad (2)$$

where d_{25} and d_{75}, refer to the particle sizes for which the recovery values on the efficiency curves correspond to 25% and 75%, respectively.

Figure 2(b) shows a comparison of the separation performance indices of the two cylindrical section hydrocyclones at different height ratios. As shown in the figure, the separation cut size d_{50} decreased from 93.2 to 76.1 μm as the height ratio increased, and the possibility deviation E_p and imperfection I tended to decrease. The value decreased significantly when the height ratio increased from 0.03 to 0.17 and decreased little when the ratio increased from 0.93 to 1.46. Therefore, increasing the height ratio reduced the separation cut size, improved the separation accuracy, and further enhanced the separation performance of two cylindrical section hydrocyclones.

3.2. Particle Spatial Distribution. The manuscript evaluates the spatial distribution of particles within the two cylindrical section hydrocyclone by investigating the enrichment ratio (λ), which is expressed as

$$\lambda = \frac{\alpha_1}{\alpha_f} \quad (3)$$

where α_1 and α_f are the volume fractions of the characteristic particles in the local grid and in the feed, respectively.

The enrichment ratio reflects the movement characteristics of the different particles during the separation process within the two cylindrical section hydrocyclone, which determines the particle compositions of the separation products. To effectively characterize the spatial distribution of the particles, the region with a volume fraction of the air phase >95% was defined as the air cone and eliminated from the simulation. The enrichment ratios of the 10, 59.5, 89, and 150 μm particles in the characteristic cross sections with different height ratios are shown in Figures 3–6, respectively.

As shown in Figure 3, the 10 μm particles were mainly enriched in the wall surface of the upper cylinder and air core regions at different height ratios. In addition, only a slight enrichment occurred around the air core in the lower cylinder. With increasing height ratio, the location of the enriched region gradually shifted upward and inward, the number of particles in the upper cylinder increased, and the probability of fine particles entering the underflow decreased, which

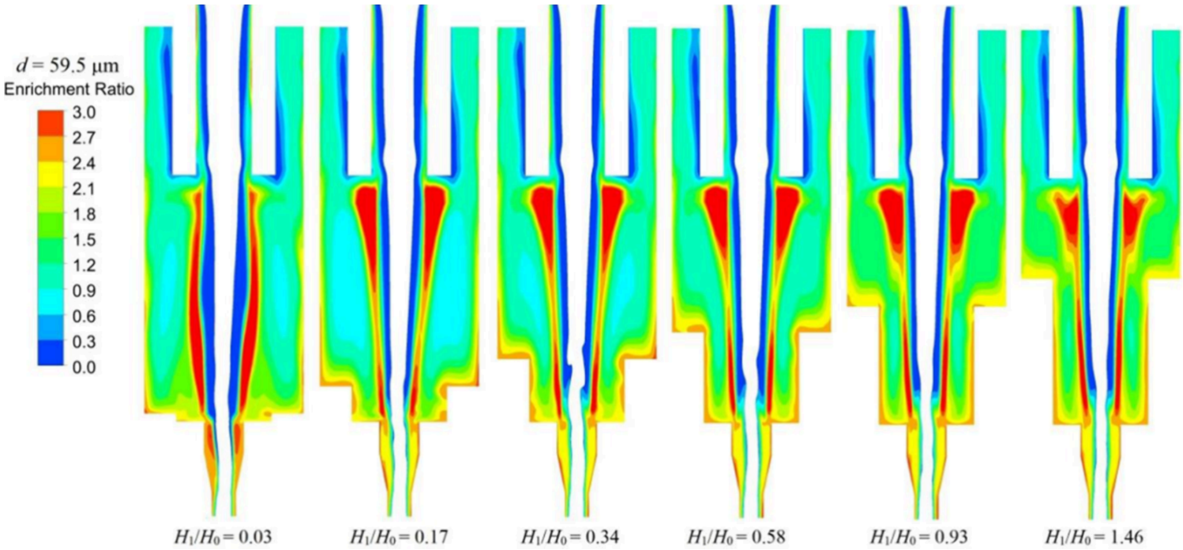


Figure 4. Effect of height ratio on the enrichment ratio of 59.5 μm particles.

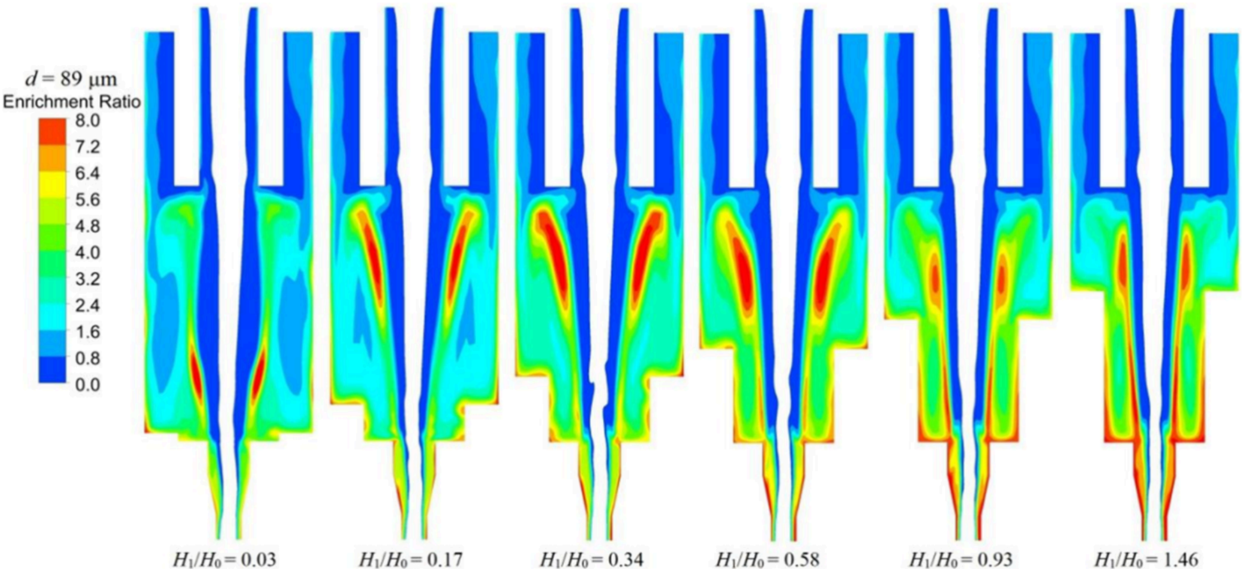


Figure 5. Effect of height ratio on the enrichment ratio of 89 μm particles

contributed to the relief of the phenomenon of fine particle misplacement in the underflow.

As shown in Figure 4, the 59.5 μm particles were mainly enriched in the air core region at the different height ratios, and the enrichment ratio was greater at the bottom of the air core when H_1/H_0 = 0.03. With increasing height ratio, an enrichment area gradually appeared under the vortex finder and showed a trend of first increasing and then decreasing. In addition, the enrichment ratio in the lower cylinder increased, which indicated that a height ratio that was too large or too small increased the likelihood of 59.5 μm particles moving downstream and affecting the fineness of the underflow.

As shown in Figure 5, the 89 μm particles were mainly enriched in the region under the vortex finder at different height ratios in the upper cylinder. The enrichment area tended to first increase and then decrease with an increasing height ratio, and the position first rose and then fell. The enriched region of the lower cylinder section was mainly around the air core and wall. The area of the enriched region gradually increased with increasing height ratio, which contributed to improving the recovery rate of this particle in the underflow, and the problem of coarse particles misplacement in overflow could be effectively relieved when $H_1/H_0 \geq$ 0.93.

As shown in Figure 6, the region that was very enriched with high 150 μm particles was mainly concentrated at the bottom of the lower cylinder of the two cylindrical section hydrocyclones at different height ratios. A large amount of medium-concentration particle enriched region existed in the upper cylinder when H_1/H_0 = 0.03, which gradually narrowed and decreased as the height ratio increased. The probability of 150 μm coarse particles entering the overflow decreased, which did not enrich in the upper cylinder when $H_1/H_0 \geq$ 0.58, further alleviating the coarse particles misplacement in the overflow.

3.3. Circulation Flow Characteristics. The circulation flow at the bottom of the hydrocyclone helps delay the particle settlement velocity, promotes the secondary grading of medium and coarse particles entrapped in the internal swirling

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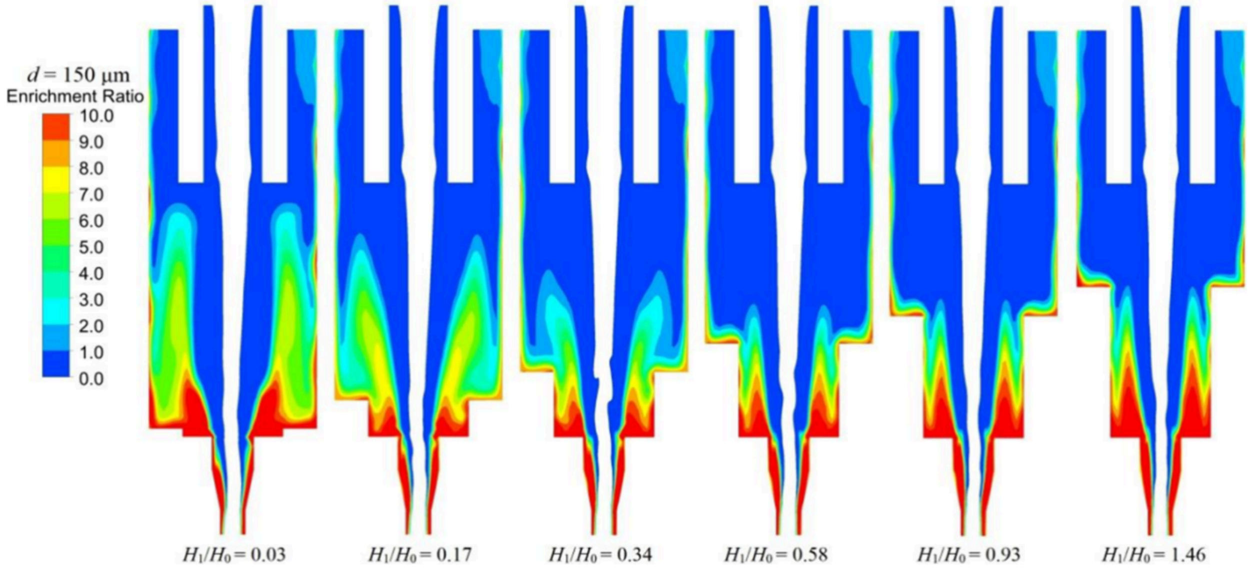

Figure 6. Effect of the height ratio on the enrichment ratio of 150 μm particles

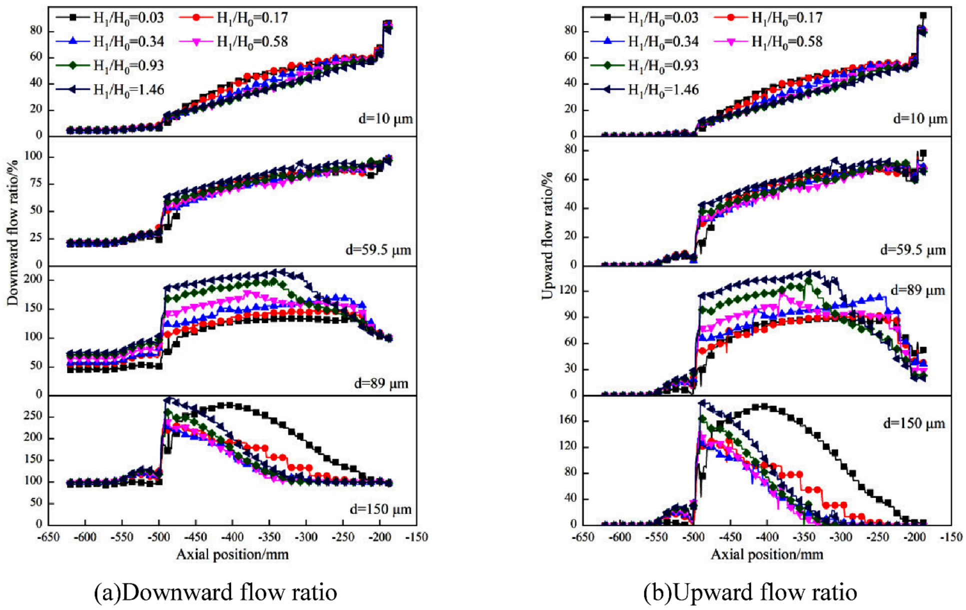

Figure 7. Effect of the height ratio on the circulation flow.

flow, and alleviates the problem of coarse particles misplacement in overflow. In this paper, the downward flow ratio and upward flow ratio were adopted to describe the characteristics of circulation flow, the calculation of which could be found in the Supporting Information. Figure 7 shows a comparison of the circulation flow characteristic curves at different height ratios.

As shown in Figure 7(a), the downward flow ratios of 10 μm particles at different height ratios decreased slightly with a decreasing axial position, which indicated that the circulation flow of fine particles stopped. Moreover, the downward flow ratios of 10 μm particles decreased gradually with increasing height ratio, which could contribute to the alleviation of fine particle misplacement in the underflow. The change in the height ratio had little impact on the downward flow ratios of the 59.5 μm particles, and the variations in these ratios were in agreement with those of the 10 μm particles. As the axial position decreased, the downstream flow ratios of the 89 μm particles tended to first increase and then decrease, which indicated that there was obvious medium particle circulation flow. Furthermore, the downstream flow ratio increased gradually with increasing height ratio. When the particle size reached 150 μm, there was coarse particle circulation flow in the hydrocyclone, but the effect of increasing the height ratio decreased.

As shown in Figure 7(b), the upward flow ratios of the 89 μm particles gradually increased with increasing the height ratio. Conversely, the upward flow ratios of the 150 μm particles tended to first decrease and then increase. This finding indicated that increasing the height ratio could be useful for strengthening the circulation flow of the medium particles. When H_1/H_0 = 0.03, there was a large upward flow of coarse particles in the upper cylinder; specifically, there was a significant circulation flow of coarse particles. Moreover, with

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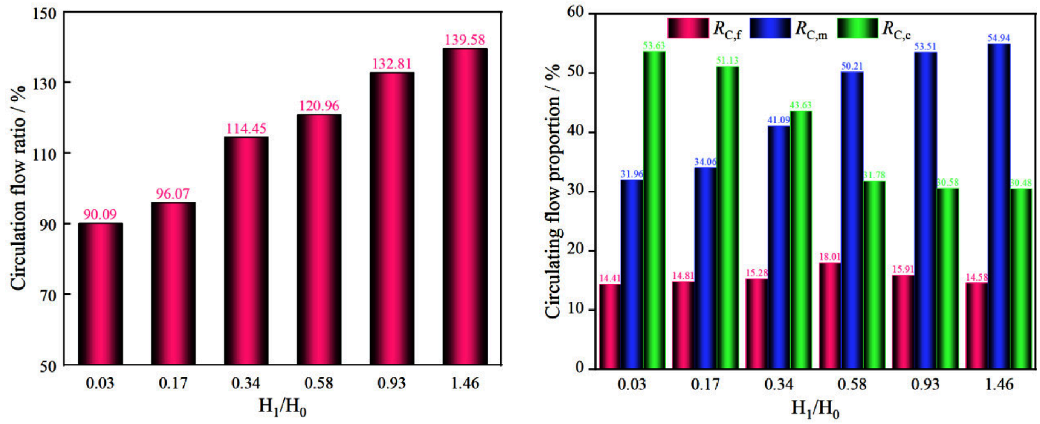

(a)Circulation flow ratio (b)Circulation flow proportion

Figure 8. Effects of height ratio on circulation flow ratio and circulation flow proportion.

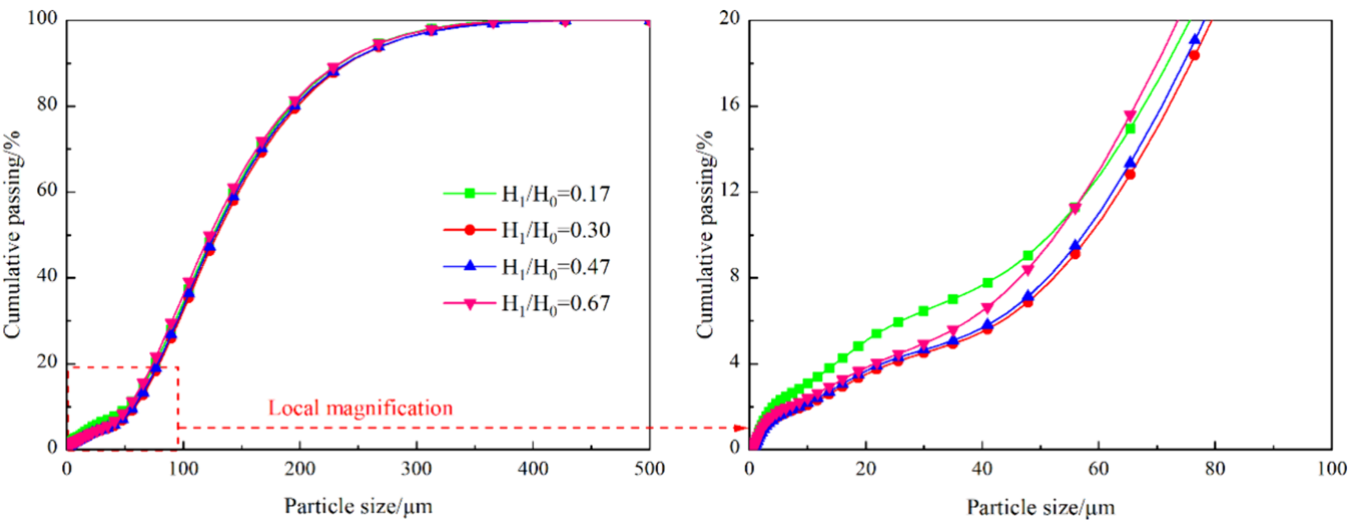

Figure 9. Effect of the height ratio on the particle size distribution in the underflow.

$H_1/H_0 \geq 0.17$, the upward flow ratios of 150 μm particles in the upper cylinder were all reduced, which indicated that the circulation of coarse particles in this region was limited. At different height ratios, the upward flow ratios of the 59.5 μm, 89 μm, and 150 μm particles in the lower cylinder all showed a trend of first increasing and then decreasing, which indicated the presence of circulation flows of medium and coarse particles at the bottom of the lower cylinder. These flows could facilitate the fine particles entrapped in the external swirling flow to re-enter the separation space and enhance the separation performance of the two cylindrical section hydrocyclone.

To quantitatively evaluate the circulation flow characteristics, we introduced the concepts of the circulation flow ratio (R_C) and proportion ($R_{C,f}$, $R_{C,m}$, and $R_{C,c}$), the calculation of which can be found in the Supporting Information. The effects of the height ratio on the circulation flow ratio and proportion are shown in Figure 8. As shown in Figure 8(a), the particle circulation flow ratio in the two cylindrical section hydrocyclone gradually increased with increasing height ratio and the growth rate gradually decreased, which indicated that increasing the height ratio contributed to increasing the circulation flow. With increasing height ratio, the particle circulation effect in the lower cylinder became increasingly evident, and the decrease in the diameter of the lower cylinder enhanced the centrifugal force field, which promoted the radial outward migration of medium and coarse particles entrained in the internal swirling flow. As shown in Figure 8(b), the number of fine particles undergoing circulation flow was relatively limited, and the change in the height ratio had little effect on it. As the height ratio increased, the amount of medium particles underwent circulation flow gradually increased, while the number of coarse particles undergoing circulation flow tended to first decrease and then increase slowly. These trends indicated that the increase in the height ratio could help to strengthen the circulation flow of medium particles while reducing the number of fine and coarse particles undergoing the circulation flow. The medium particle circulation flow gradually dominated when $H_1/H_0 \geq 0.34$.

4. PHYSICAL TESTS

In this paper, under the assumption that the operating and structural parameters were consistent, we conducted an experimental study of a two cylindrical section hydrocyclone concerning the height ratio H_1/H_0 = 0.17−0.67 and used the particle size distributions and separation performance of the exported products as evaluation indices for validation and analysis. The experimental equipment, experimental process,

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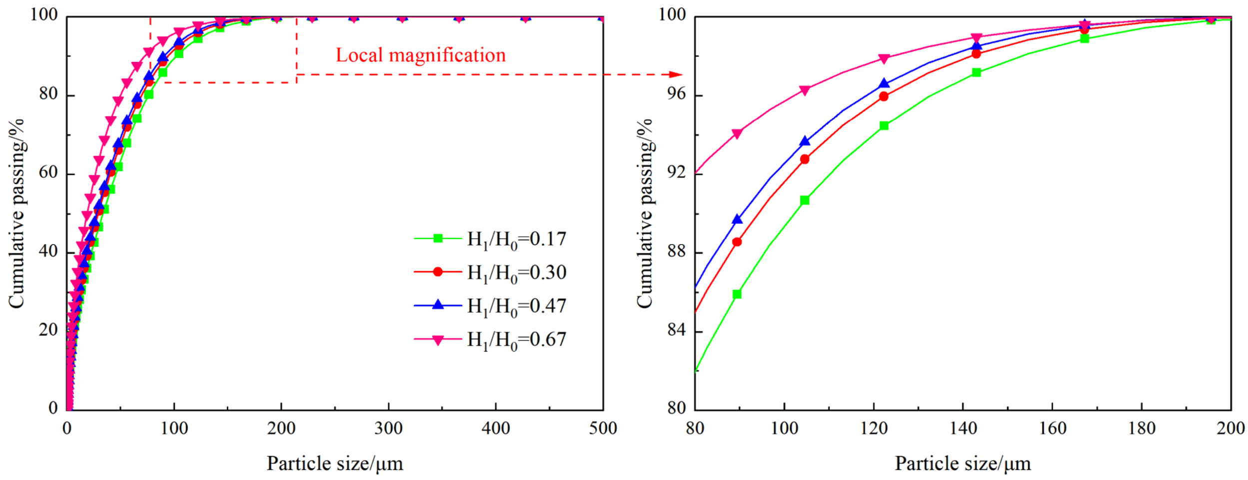

Figure 10. Effect of the height ratio on the particle size distribution in overflow

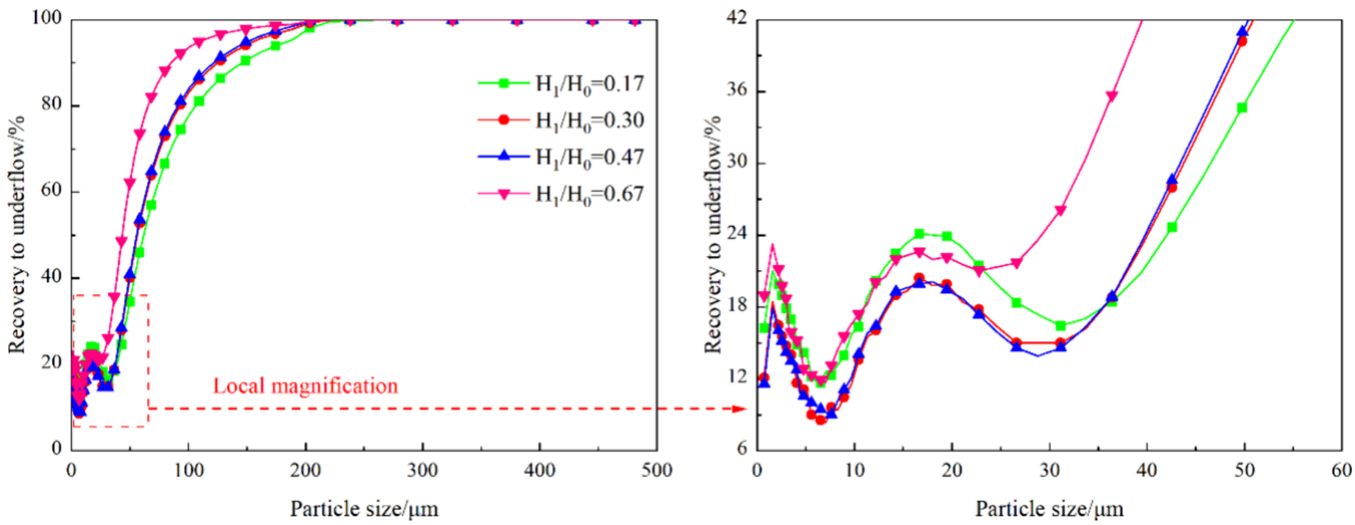

Figure 11. Effect of the height ratio on the efficiency curve.

material characteristics, and evaluation methods can be found in the Supporting Information.

4.1. Particle Size Distribution. The particle size distribution curve presents the coarse and fine characteristics of the separation products of the hydrocyclone, reflecting the number of misplaced particles in the under- or overflow. Figures 9 and 10 show comparisons of the particle size distribution curves of the under- and overflow, respectively, under the change in the height ratio.

As shown in Figure 9, with increasing height ratio, the cumulative curve of the underflow of the two cylindrical section hydrocyclones shifted first to the right and then to the left, and the recovery ratio of fine particles in the underflow first decreased and then increased. This result indicated that appropriately increasing the height ratio could help to alleviate fine particle misplacement in the underflow. The particle size of the underflow was the coarsest when H_1/H_0 = 0.30. With increasing height ratio, the radial settling distance of fine particles in the lower cylinder decreased, the effect of external swirling flow on fine particle accumulation increased, and the number of fine particles in the underflow increased. As shown in Figure 10, with increasing height ratio, the medium particle size of the overflow decreased by 14.8 μm, the cumulative curve shifted to the left, and the content of coarse particles in the overflow decreased by 3.68% for particles with sizes greater than 122 μm. This result indicated that increasing the height ratio could help to alleviate the problem of coarse particle misplacement in overflow, which was consistent with the conclusion drawn from the simulation results.

4.2. Separation Performance. Figure 11 shows a comparison of the efficiency curves at different height ratios obtained from the test. As shown in the figure, with increasing height ratio, the recovery rates of fine particles in the underflow first decreased and then increased in the two cylindrical section hydrocyclone, which was consistent with the change in the particle size characteristics of the underflow. The recovery rate of coarse particles gradually increased, and the coarse particles misplacement in overflow was alleviated. With increasing height ratio, the overall separation space in the hydrocyclone decreased, the increase in the tangential velocity strengthened the radial arrangement of the particles, and the radial settlement distance of the particles in the lower cylinder decreased because of the relatively small diameter of the lower cylinder. The greater the height ratio, the greater the amount of space occupied by the minimum radial settling distance, which contributed to facilitating the return of mismatched particles in the internal swirling flow to the external swirling

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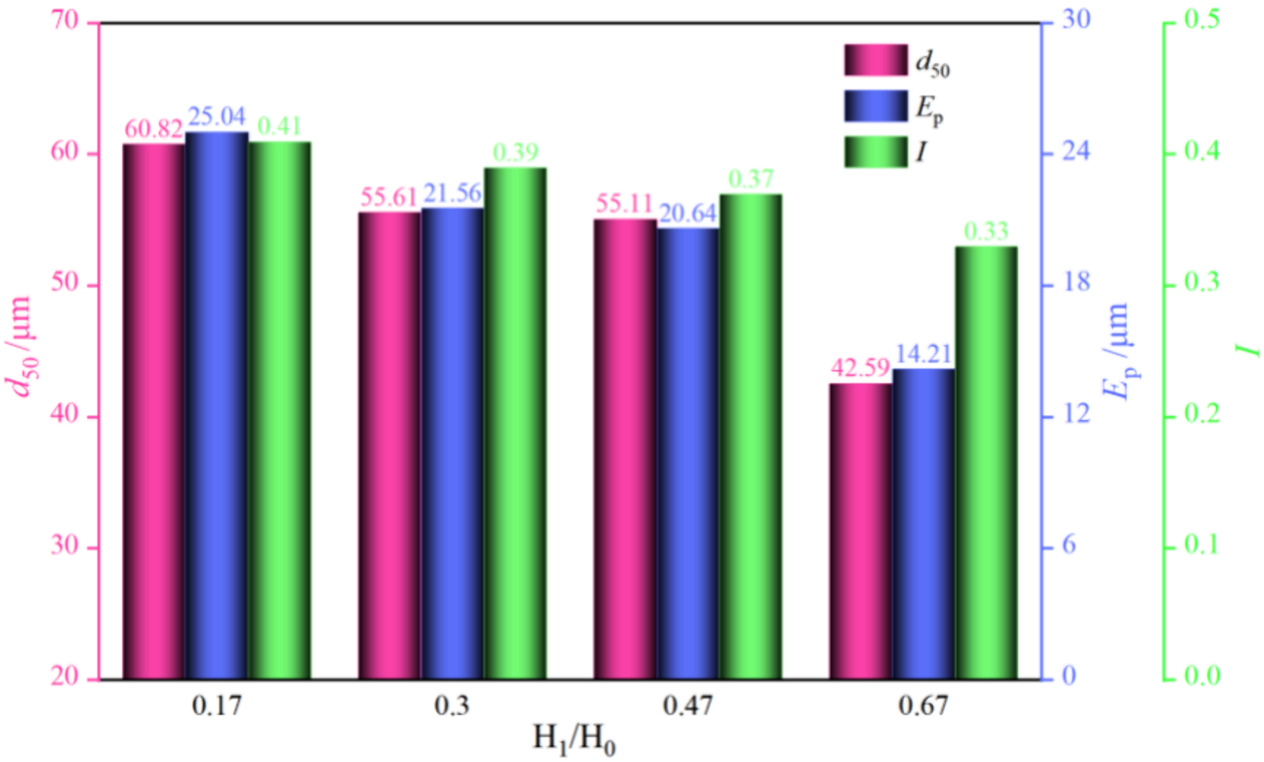

Figure 12. Effect of the height ratio on the separation performance index

flow and to improving the separation performance of the two cylindrical section hydrocyclone.

In this paper, we selected the separation cut size d_{50}, possible deviation E_p, and imperfection I value to quantitatively evaluate the efficiency curves, and the changes are shown in Figure 12. With increasing height ratio, the d_{50} of the two cylindrical section hydrocyclone decreased, and the d_{50} decreased by 12.52 μm when the height ratio increased from 0.47 to 0.67. This result further illustrated that an increase in the height ratio increased the recovery rate of fine particles in the underflow and decreased the separation cut size of the hydrocyclone. E_p and I also decreased gradually and uniformly, which indicated that increasing the height ratio could help to improve the separation accuracy, reduce the number of misplaced particles in the separation products, and enhance the separation effect of the two cylindrical section hydrocyclone.

Table 2 shows the effect of the height ratio on the classification performance of the hydrocyclones. We introduced ε_u (this parameter represents particles with sizes of less than 23 μm in the underflow) to reflect fine particle misplacement in the underflow and ε_o (this parameter represents particles with sizes of more than 154 μm in the overflow) to reflect coarse particle misplacement in the overflow. Additionally, we calculated the integrated classification efficiency of a specific particle size. As shown in the table, with increasing height ratio, the number of fine particles in the underflow of the two cylindrical section hydrocyclones first decreased and then increased. The number of misplaced particles in the underflow decreased the least when H_1/H_0 = 0.3. Moreover, the amount of coarse particle misplacement in overflow gradually decreased, which was consistent with the above conclusions. With increasing height ratio, the classification efficiency of particles with sizes of less than 23 μm increased, and the classification efficiency of particles with sizes of less than 74 μm first increased and then decreased, reaching a maximum at H_1/H_0 = 0.47. Furthermore, the classification efficiency of particles with sizes of less than 154 μm showed a fluctuating tendency, reaching a maximum at H_1/H_0 = 0.17. This result indicated that large height ratios facilitated the classification of fine particles, and small height ratios facilitated the classification of coarse particles.

Table 2. Effect of Height Ratio on the Classification Performance

H_1/H_0	ε_u/%	ε_o/%	E_{-23}/%	E_{-74}/%	E_{-154}/%
0.17	5.12	1.85	52.74	58.28	45.93
0.30	3.55	1.15	61.38	60.07	39.38
0.47	3.70	0.86	61.31	61.85	43.63
0.67	3.87	0.67	67.49	54.81	30.71

5. CONCLUSIONS

To reduce the number of misplaced particles in separation products and improve the separation accuracy of hydrocyclones, we adopted a numerical simulation method to investigate the particle motion behaviors of two cylindrical section hydrocyclones with various height ratios by applying evaluation indices of separation performance, particle spatial distribution, and circulation flow characteristics. Moreover, we conducted physical tests for verification, which led to the following conclusions:

1. The effect of the height ratio on the separation performance of fine particles could be neglected in two cylindrical section hydrocyclones. As the height ratio increased, the recovery of medium and coarse particles in the underflow increased, the separation cut size

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decreased, and the separation accuracy gradually improved.

2. Within the two cylindrical section hydrocyclone, obvious circulation flow of the medium and coarse particles was observed. With increasing height ratio, the proportion of medium particle circulation flow gradually increased, the enrichment ratios of the 59.5 and 89 μm particles in the lower cylinder gradually increased, and the enrichment ratio of the 150 μm particles in the upper cylinder gradually decreased. The circulation flow of medium particles was dominant when $H_1/H_0 \geq 0.34$, which could help to alleviate coarse particles misplacement in overflow.
3. When $H_1/H_0 = 0.30$, the number of fine particles in the underflow was the lowest. With increasing height ratio, the recovery rates of fine particles in the underflow tended to first decrease and then increase. Furthermore, the classification efficiency of fine particles gradually improved. The height ratios were 0.47 and 0.17, which represented the highest separation efficiencies for medium and coarse particles, respectively. Therefore, optimizing the height ratio could improve the separation performance of the two cylindrical section hydrocyclone.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.4c02365.

Mesh verification, model description, model applicability, circulation flow characteristics, physics tests device and conditions (PDF)

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Notes

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■ REFERENCES

(1) He, L.; Ji, L.; Sun, X.; Chen, S.; Kuang, S. Investigation of mini-hydrocyclone performance in removing small-size microplastics. *Particuology.* **2022**, *71*, 1−10.

(2) Colli, A. N.; Fornés, J. P.; González Pérez, O.; Bisang, J. M. Evaluation of a modified hydrocyclone as electrochemical reactor for processing of two-phase (gas-liquid) systems. *Electrochim. Acta* **2019**, *309*, 219−227.

(3) Saengchan, K.; Nopharatana, A.; Songkasiri, W. New hydrocyclone design for high starch yield: Effect of cylindrical-conical length proportion on the starch, sulfur and protein separation efficiencies. *Powder Technol.* **2019**, *346*, 1−8.

(4) Niazi, S.; Habibian, M.; Rahimi, M. Performance evaluation of a uniflow mini-hydrocyclone for removing fine heavy metal particles from water. *Chem. Eng. Res. Des.* **2017**, *126*, 89−96.

(5) Liu, P.; Fu, W.; Jiang, L.; Zhang, Y.; Yang, X.; Li, X.; Wang, H. The separation performance of a parabolic hydrocyclone in separating iron from red mud. *Powder Technol.* **2023**, *416*, No. 118205.

(6) Palaniandy, S.; Yahyaei, M.; Powell, M. Assessment of hydrocyclone operation in gravity induced stirred mill circuits. *Miner. Eng.* **2017**, *108*, 83−92.

(7) Ji, L.; He, L.; Chu, K.; Kuang, S. How Particles with Sizes Close to Cut Size Affect the Multiphase Flows and Performance of Hydrocyclones. *Ind. Eng. Chem. Res.* **2021**, *60*, 18477−18489.

(8) Kashiwaya, K.; Noumachi, T.; Hiroyoshi, N.; Ito, M.; Tsunekawa, M. Effect of particle shape on hydrocyclone classification. *Powder Technol.* **2012**, *226*, 147−156.

(9) Gonçalves, S. M.; Ullmann, G.; Morimoto, M.G.; de Souza Barrozo, M. A.; Vieira, L. G. M. Effect of rheology and solids concentration on hydrocyclones performance: A study involving the design variables of an optimized hydrocyclone. *J. Pet. Sci. Eng.* **2022**, *210*, 110019.

(10) Hou, D.; Cui, B.; Zhao, Q.; Wei, D.; Song, Z.; Feng, Y. Research on the structure of the cylindrical hydrocyclone spigot to mitigate the misplacement of particles. *Powder Technol.* **2021**, *387*, 61−71.

(11) Vakamalla, T.R.; Mangadoddy, N. The dynamic behaviour of a large-scale 250-mm hydrocyclone: A CFD study. *Asia-Pacific J. Chem. Eng.* **2019**, *14*, e2287.

(12) Ye, J.; Xu, Y.; Song, X.; Yu, J. Numerical modelling and multi-objective optimization of the novel hydrocyclone for ultra-fine particles classification. *Chem. Eng. Sci.* **2019**, *207*, 1072−1084.

(13) Kyriakidis, Y. N.; Silva, D. O.; Barrozo, M. A. S.; Vieira, L. G. M. Effect of variables related to the separation performance of a hydrocyclone with unprecedented geometric relationships. *Powder Technol.* **2018**, *338*, 645−653.

(14) Patra, G.; Velpuri, B.; Chakraborty, S.; Meikap, B. C. Performance evaluation of a hydrocyclone with a spiral rib for separation of particles. *Adv. Powder Technol.* **2017**, *28*, 3222−3232.

(15) Ji, L.; Kuang, S.; Yu, A. Numerical Investigation of Hydrocyclone Feed Inlet Configurations for Mitigating Particle Misplacement. *Ind. Eng. Chem. Res.* **2019**, *58*, 16823−16833.

(16) E, D.; Fan, H.; Su, Z.; Xu, G.; Zou, R.; Yu, A.; Kuang, S. Numerical study of the multiphase flows and separation performance of hydrocyclone with tapered cross-section inlet. *Powder Technol.* **2023**, *416*, No. 118208.

(17) Pathak, S. S.; Mishra, S.; Tyeb, M. H.; Majumder, A. K. Spigot Design Modification to Alleviate Roping in Hydrocyclones, Mining, Metall. *Explor.* **2022**, *39*, 761−775.

(18) Jiang, L.; Liu, P.; Yang, X.; Zhang, Y. Short-Circuit Flow in Hydrocyclones with Arc-Shaped Vortex Finders. *Chem. Eng. Technol.* **2018**, *41*, 1783−1792.

(19) Goncalves, S. M.; Kyriakidis, Y. N.; Ullmann, G.; Barrozo, M. A. d. S.; Vieira, L. G. M. Design of an Optimized Hydrocyclone for High Efficiency and Low Energy Consumption. *Ind. Eng. Chem. Res.* **2020**, *59*, 16437−16449.

(20) Ghodrat, M.; Qi, Z.; Kuang, S. B.; Ji, L.; Yu, A. B. Computational investigation of the effect of particle density on the

multiphase flows and performance of hydrocyclone. *Miner. Eng.* **2016**, *90*, 55−69.
(21) Dou, D.; Qiu, Z.; Yang, J. Parameter optimization of an industrial water injection hydrocyclone in the Taixi coal preparation plant. *Int. J. Coal Prep. Util.* **2022**, *42*, 2357−2365.
(22) Zhou, Q.; Wang, C.; Wang, H.; Wang, J. Eulerian-Lagrangian study of dense liquid-solid flow in an industrial-scale cylindrical hydrocyclone. *Int. J. Miner. Process.* **2016**, *151*, 40−50.
(23) Lu, X.; Yang, X. A research on separation mechanism of Cylindrical Hydrocyclone. *Adv. Mater. Res.* **2012**, *455*−*456*, 69−73.
(24) Jiang, L.; Liu, P.; Zhang, Y.; Yang, X.; Wang, H.; Gui, X. Design boundary layer structure for improving the particle separation performance of a hydrocyclone. *Powder Technol.* **2019**, *350*, 1−14.
(25) Jiang, L.; Liu, P.; Yang, X.; Zhang, Y.; Li, X.; Zhang, Y.; Wang, H. Experimental research on the separation performance of W-shaped hydrocyclone. *Powder Technol.* **2020**, *372*, 532−541.
(26) Hou, D.; Zhao, Q.; Liu, P.; Jiang, L.; Cui, B.; Wei, D. Effects of bottom profile on the circulation and classification of particles in cylindrical hydrocyclones. *Adv. Powder Technol.* **2023**, *34*, No. 104050.
(27) Hou, D.; Zhao, Q.; Cui, B.; Wei, D.; Song, Z.; Feng, Y. Geometrical configuration of hydrocyclone for improving the separation performance. *Adv. Powder Technol.* **2022**, *33*, No. 103419.
(28) Al Kayed Quteishat, M. Hydrocyclone flow characteristics and measurements. *Flow Meas. Instrum.* **2020**, *73*, No. 101741.
(29) Wang, J.; Bai, Z.; Yang, Q.; Fan, Y.; Wang, H. Investigation of the simultaneous volumetric 3-component flow field inside a hydrocyclone. *Sep. Purif. Technol.* **2016**, *163*, 120−127.
(30) Diddi, S.; Jampana, P. V.; Mangadoddy, N. Evaluation of Two Noniterative Electrical Resistance Tomography (ERT) Reconstruction Algorithms for Air-Core Measurements in Hydrocyclone. *Ind. Eng. Chem. Res.* **2022**, *61*, 18017−18029.
(31) Vega-Garcia, D.; Brito-Parada, P. R.; Cilliers, J. J. Optimising small hydrocyclone design using 3D printing and CFD simulations. *Chem. Eng. J.* **2018**, *350*, 653−659.
(32) Zhao, Q.; Cui, B.; Shen, Y.; Liu, W.; Zhao, S.; Feng, Y. Understanding the characteristics and functions of axial velocity fluctuation zone in hydrocyclones: part 1 flow pattern. *Chem. Eng. Sci.* **2024**, *283*, No. 119368.
(33) Narasimha, M.; Brennan, M.; Holtham, P. N. A Review of CFD Modelling for Performance Predictions of Hydrocyclone. *Eng. Appl. Comput. Fluid Mech.* **2007**, *1*, 109−125.
(34) Qiu, Z.; Zhou, L.; Bai, L.; El-Emam, M. A.; Agarwal, R. Empirical and numerical advancements in gas-liquid separation technology: A review. *Geoenergy Sci. Eng.* **2024**, *233*, No. 212577.
(35) Li, Z.; Tong, Z.; Zhang, H.; Chu, K.; Li, R.; Miao, H.; Zhao, J.; Yu, A. CFD-DEM simulation of the supercritical water-solid flow in cyclone. *Powder Technol.* **2023**, *418*, No. 118261.
(36) Kumar, M.; Reddy, R.; Banerjee, R.; Mangadoddy, N. Effect of particle concentration on turbulent modulation inside hydrocyclone using coupled MPPIC-VOF method. *Sep. Purif. Technol.* **2021**, *266*, No. 118206.
(37) Padhi, M.; Mangadoddy, N.; Sreenivas, T.; Vakamalla, T. R.; Mainza, A. N. Study on multi-component particle behaviour in a hydrocyclone classifier using experimental and computational fluid dynamics techniques. *Sep. Purif. Technol.* **2019**, *229*, No. 115698.
(38) Hou, D.; Zhao, Q.; Cui, B.; Wei, D.; Song, Z.; Feng, Y. The effects of solid shear stress and wall roughness on the simulation of cylindrical hydrocyclone classification. *Powder Technol.* **2021**, *393*, 184−204.
(39) Yu, J.; Luo, X.; Wang, B.; Wu, S.; Wang, J. Analysis of Gas-Liquid-Solid Three-Phase Flows in Hydrocyclones through a Coupled Method of Volume of Fluid and Discrete Element Model. *J. Fluids Eng. Trans. ASME* **2021**, *143*, 111402.
(40) Razmi, H.; Soltani Goharrizi, A.; Mohebbi, A. CFD simulation of an industrial hydrocyclone based on multiphase particle in cell (MPPIC) method. *Sep. Purif. Technol.* **2019**, *209*, 851−862.

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