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Research on the action mechanism of air core and experiments of separation performance inside multi-product cyclone with double vortex finders

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Narrow particle size separation is one of the principal means in boosting the efficiency and accuracy of beneficiation, with cyclone as currently the main equipment for particle classification. The traditional hydrocyclone can only obtain two products: overflow and underflow, which is not able to meet the requirements of fine classification. A new multi-product cyclone was proposed to improve the separation precision and efficiency. This multi-product cyclone was constitute of two-stage series: the primary cyclone which contains two coaxial overflow tubes with different diameters and the secondary general cyclone. Then, by utilizing the numerical simulation, the action mechanism of air column in the cyclone with two overflow tubes was researched according to a new flow field model. Finally, a "three-level-four-factor" orthogonal experiment of measuring the separation effect and the influence factors was carried out. Results show that one classification can obtain four different narrow-grade-classification products: primary underflow, primary overflow, secondary underflow, and secondary overflow. The formation and evolution process of the air core inside of two-overflow-tube cyclone is an important symbol of the stable flow field. The structural parameters and operating pressure are proven to play a significant role in the separation precise and efficiency of the multi-product cyclone. The experiments demonstrate that the proposed cyclone is effective for separation efficiency, The research results can provide a good guidance for separation performance and industrial application of multi-product cyclone separator.

Keywords: Multi-product cyclone , Numerical simulation, Orthogonal experiments.

INTRODUCTION

Narrow-grade-classification is one of the important methods in improving the efficiency and accuracy of beneficiation, with cyclone as currently the main equipment for particle classification [1]. cyclones have been widely used as particle size classification, density separation, slurry concentration and liquid clarification apparatus on solid-liquid flow in the field of mineral processing [2], coal engineering [3], chemical engineering [4], and process industries [5] because of their simple structure, absence of moving parts, high separation efficiency, large work capacity, small separation size, low investment, low maintenance costs and no environment pollution [6~8]. Plenty of parameters can affect the performance of the flow field of cyclones. Among all the parameters, structural style and structural parameters are factors having a great impact on the separation performance of cyclones [9~11]. So study of the influence of structural style and structural parameters of a cyclone on its flow field distribution and separation performance plays a deterministic role in the optimization of a cyclone's design and its normal operation [12~14]. In order to improve the separation performance of cyclones and meet the requirements of different industries, domestic and foreign scholars have designed cyclones of various structural styles, and conducted in-depth researches on their structural parameters.

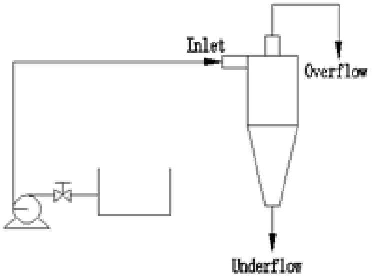

Fig. 1. Classification diagram of the traditional cyclone

From the literature research, it reveals that traditional cyclones [15~17] can only get two products from a single classification, as shown in Fig.1. Owing to it's over broad definition of product particle grading range, this method was not able to meet the requirements of fine classification. To solve the problem of over broad range and obtain products with more categories of narrow particles, people usually connect several cyclones in series, as shown in Fig.2.

Although this process flow obtained four products of different sizes, it requires in addition 2 cyclones, 2 slurry pumps, which causes issues like long process flow, high investment in equipment, high energy consumption, etc. How could a cyclone obtain multiple products with narrow grading from

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a single classification, so as to satisfy the requirement of different separation equipment on the size range of feed particles, D.P. Obeng et al. [18, 19], Mainza A. et al. [20], Ahmed et al. [21] proposed a three-product cyclone with two coaxial vortex-finder of different diameters, and three different size narrow-grade-classification products were obtained.

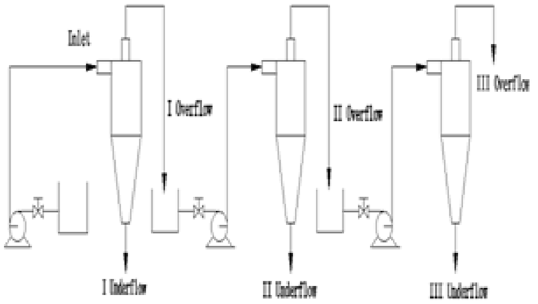


Fig. 2. Classification diagram of the three-stage multi product cyclone.

However, Investigation of a multi-product cyclone separator is seldom reported in existing literature. Structural parameters of cyclone and inlet operating pressure have a great effect on separation efficiency of the cyclone during use in power plants. All the mentioned above studies did not research the forming mechanism of the air core and did not consider the influence of structural parameters and operating pressure on the separation efficiency. Thus, improved work must be studied to examine the influence of the structural parameters and operating pressure on separation precise and classification efficiency of the cyclone with double vortex finders.

How a cyclone could obtain multiple products with narrow grading particles from the one-step classification, has become an urgent research problem. Therefore, the paper proposed a two-stage series multi-product hydrocyclone, as shown in Fig.3.

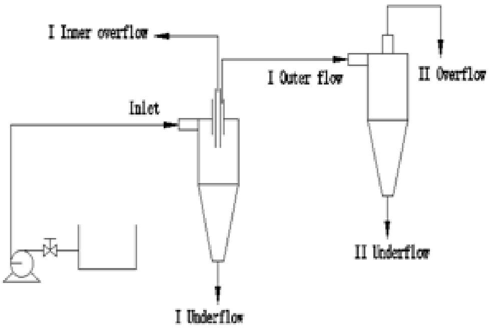


Fig. 3. Classification diagram of the multi-product cyclone.

The stage I cyclone was designed as a coaxial double vortex finders structure with different diameters. During overflow, light and fine particles exit from the inner vortex finder. The mid-size particles overflow from the outer overflow tube into the secondary cyclone. Finer classification can be obtained under the effect of residual pressure. Therefore, one-step classification can obtain four different narrow-grade-classification products: Stage I underflow, Stage I overflow, Stage II underflow, and Stage II overflow.

EXPERIMENTAL

Stage I of the cyclone is designed as a coaxial double-overflow-pipe structure, with the structural drawing sketched in Fig.4 and the structural parameters specified in Table1.

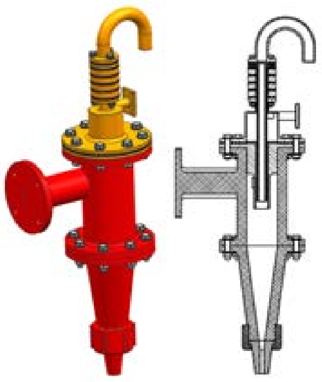


Fig. 4. Main structural parameters of the cyclone.

Table 1. Main structural parameters of the cyclone with double vortex.

Structural parameter	Structural dimensions
Hydrocyclone diameter (mm)	50
Inner vortex finder diameter (mm)	5, 6, 7, 9, 10
Outer vortex finder diameter (mm)	20
Underflow port diameter (mm)	6, 8, 10, 12
Feed inlet equivalent diameter (mm)	12
Outer overflow pipe insertion depth (mm)	85
Inner overflow pipe insertion depth (mm)	65, 75, 85, 95, 105
Cylinder height (mm)	116
Total height (mm)	310
Cone angle of hydrocyclone (°)	15

Fig. 5. The general cyclone

Fig. 6. Multi-product cyclone

Stage II of the cyclone adopts the conventional conical or cylindrical structure with a diameter of 25 mm, as shown in Fig.5. A multi-product cyclone is created by joining the two stages of cyclones, as shown in Fig. 6.

Fig.7 shows the calculation region model of double overflow pipe cyclones. The hexahedral structure grid was used in the calculation flow field, the meshing results of the cyclone were obtained as shown in Fig. 8 and total grid number was 145087 in the model of the double vortex finders cyclone.

The boundary conditions are defined as follows:

The inlet boundary condition: The inlet was set as the velocity inlet condition with a fluid velocity of 5 m/s.

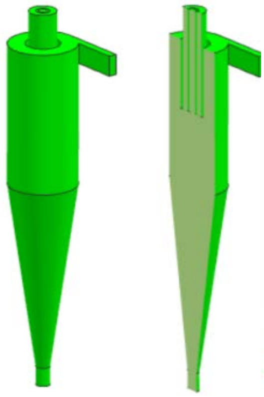


Fig. 7. The calculation Flow field model

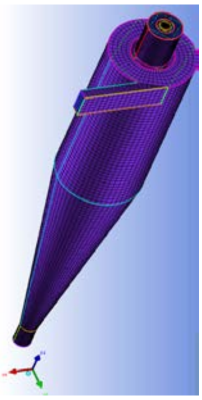


Fig. 8. Meshes of the cyclone

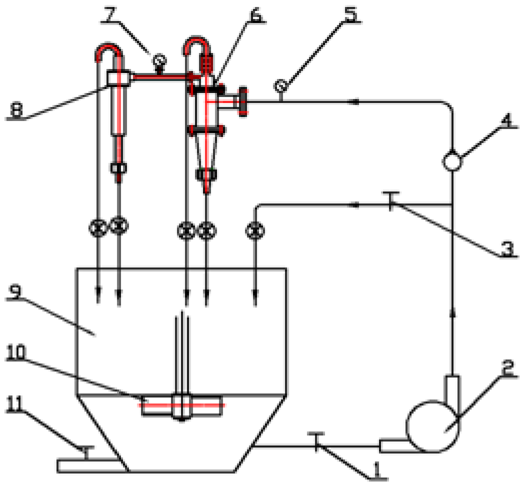
The outlets boundary condition: The pressure outlet boundary condition was applied for the both overflow and underflow ports boundary.

Wall modification condition: The near wall surface modification was simulated by “Standard Wall Functions”.

The discretization schemes are selected as follows:

Governing equations were solved by the finite volume method using the FLUENT software 6.3. In the numerical simulations, the “SIMPLE” pattern was selected for the pressure-speed coupling. the pressure discretization of the governing equations were used the “PRESTO” method. The Reynolds stress discretization was solved by the first-order upwind scheme and the momentum discretization was selected the “QUICK” method. Besides, VOF (Volume of Fluid) flow model was adopted to capture the interface between air and water in the cyclone. The primary phase was set as water while the secondary phase was set as air.

Testing method



1-Valve, 2-Pump, 3-Valve, 4-Flowmeter, 5-Pressure gauge, 6-Hydrocyclone,
7-Pressure gauge, 8-Hydrocylone, 9-Mixing tank, 10-Mixing impeller,11-Valve.

Fig. 9. Test system diagram.

Fig. 10. The test site image of the cyclone.

Fig.9 and Fig.10 is respectively the testing system sketch and local test image. The testing system consists of pumps, valves, pressure gauges, flow meters and the multi-product cyclone, etc. The slurry pump extracted the prepared fly ash slurry from the slurry pool, through adjustment of the opening of the reflux valve and the frequency converter, stabilized the pressure at the test required inlet pressure value. After the system operated normally, we sampled at the overflow port and also at the underflow port. By using equipment like vacuum pumping and filtering system, dry box, electronic scales for test use and laser particle size analyzer, we measured the slurry concentration, particle size, flow rate, and other indices of the outputted products.

After the cyclone run stability for about 10 minutes, we sampled respectively from the underflow outlet port and overflow outlet port of the hydrocyclone, and assessed the concentration and particle size of the products. During the analysis on the collected samples, two parallel measurements were conducted on the same specimen. If the difference of the two measurements did not exceed the error tolerance of the same test, we took the arithmetic mean of them as the final results.

RESULTS AND DISCUSSION

Action mechanism of air core inside cyclone and influence of underflow diameter on the air column

The underflow port of a cyclone is one of the important factors that affect its separation index. In particular, the diameter of the underflow port has a significant effect on the cyclone's separated particle size and product distribution, which makes the study of the effect of underflow diameter on flow field especially important. In the paper, taking a double vortex finders cyclone as the research object, the study used software FLUNT6.3. A cyclone is selected with an overflow pipe diameter of 6 mm and an inserted depth of 85 mm. Five different working conditions are investigated with the underflow diameters configured to be 6 mm, 8 mm, 10 mm and 12 mm respectively. The formation mechanism of the air column in the cyclone and the effect of underflow diameter on the properties of the air column are discussed.

Fig.11(a) to Fig.11(d) demonstrate the forming and developing processes of the air column in a double-overflow-pipe cyclone corresponding to different underflow diameters of 6 mm, 8 mm, 10 mm and 12 mm. Initially the cyclone is full of air (blue area). With the development of the flow field, the internal space of the cyclone is gradually filled by liquid (red area). When negative pressure appears in the center of the cyclone, air enters the cyclone from its overflow and underflow ports, and gradually runs through the axis of the cyclone. It can be seen from the figures that, the air column fluctuates and appears unstable when air just begins to run through; ultimately it stabilizes and becomes complete with the progress of separation process, which means that a stable flow field is generated. Regarding the formation and development mechanism of air column, researchers always hold different opinions. However, it can be concluded through the simulation done in this paper that, the overflow and underflow ports contribute in generating the air column, and the negative pressure in the cyclone is the necessary condition for the formation of air column. It can also be observed from the figures that, the axis of the air column almost coincides with the axis of the cyclone. In addition, the size and shape of the air column changes with the development of the flow field. Even after the flow field stabilizes, the air column still has different diameters at different axial positions, which shows the maximum value at the bottom of the overflow pipe. The diameter of the air column gradually becomes smaller in the overflow pipe until it reaches the junction of the pipe and cone, where obvious disorder occurs to the air column diameter. The paper attributes the variations in the size and shape of the air column to, on one hand the instability of the flow field, on the other hand the structure variation of the cyclone itself.

The formation time of air columns corresponding to cyclones with different underflow diameters is also analyzed. For underflow diameters of 6mm, 8mm, 10mm and 12mm, the formation of air column requires 1.9 s, 1.8 s, 1.65 s, and 1.6 s respectively. It indicates that a bigger underflow port requires a shorter period of time to generate the air column. From another point of view, due to the constant taper angle of the cyclone, a bigger underflow diameter implies a shorter distance between the underflow and overflow ports. So it takes a shorter time for the air column to run through between the underflow and overflow ports, and the formation of the air column becomes easier.

Orthogonal test results and discussion

The main factors affecting the performance of a multi-product cyclone are: underflow port diameter, inner overflow pipe diameter, inner overflow pipe insertion depth and feed pressure.

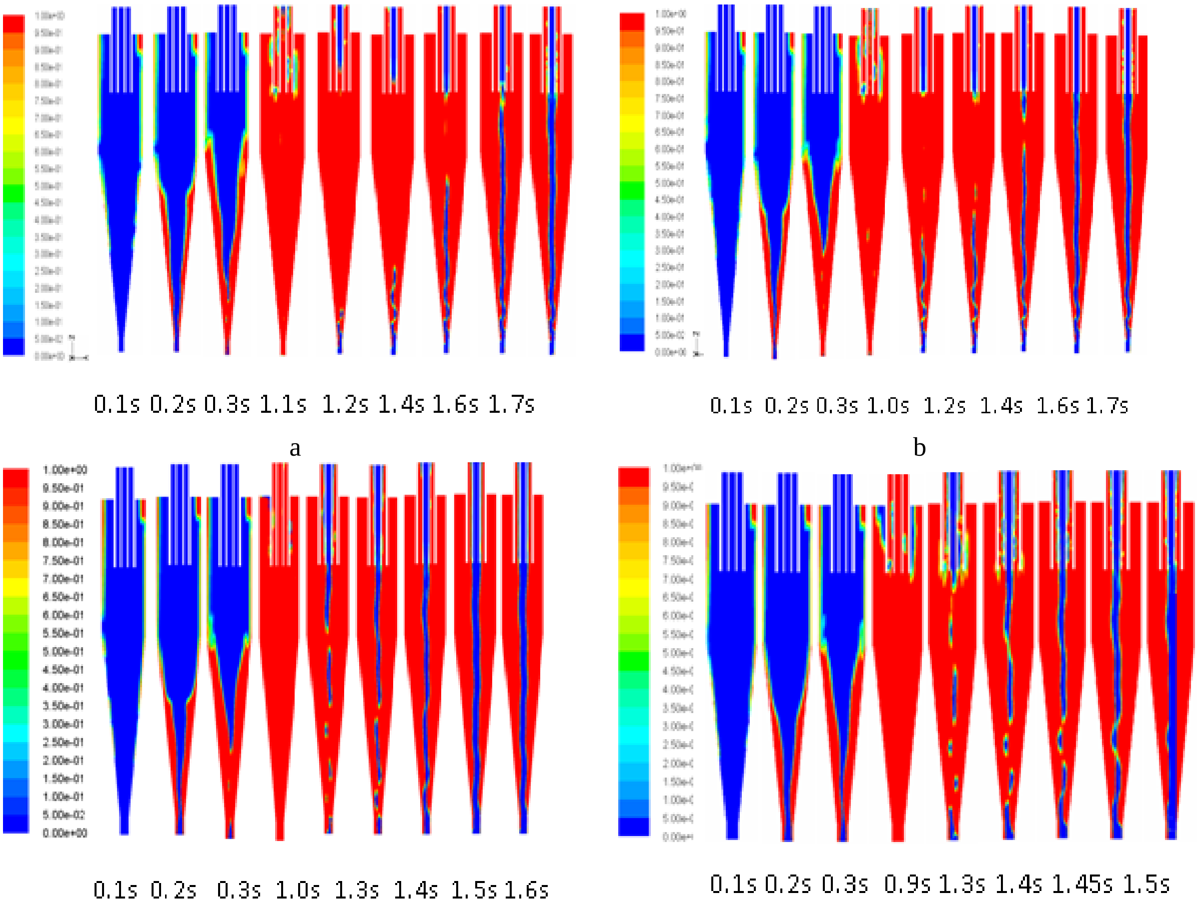
Such many combinations of structure parameters and operation parameters will undoubtedly require many tests and lots of work. In order to reduce the number of tests without compromising the test credibility, the paper conducted orthogonal test to comprehensively evaluate and analyze the influential factors, to find the primary and secondary factors affecting the separation performance, and determine the best parameter combination of the hydrocyclone.

In this paper, we carried out a three-level four-factor test with the corresponding parameter values as follows: Underflow port diameter (6mm, 10mm, 14mm); Overflow pipe insertion depth (65mm, 85mm, 105mm); Overflow pipe diameter (5mm, 7mm, 9mm); Pressure (0.12MPa, 0.16MPa, 0.20MPa).

Following the testing plan of the orthogonal experiment table, we deployed Stage I underflow yield as the single evaluation indices, conducted numerical analysis on the raw data obtained from test results, and derived the processed test results shown in table 2.

Table 2 presented the orthogonal test results of a multi-product hydrocyclone taking underflow yield as the evaluation index. By analysis, we can draw the following conclusion. The best structure parameters and inlet pressure of a multi-product hydrocyclone are: underflow pipe diameter 14mm (A3), overflow pipe insert depth 105mm (B3), overflow pipe diameter 9mm (C3), inlet pressure 0.20MPa (D3).

Comparing the average peak value R, we can see that the underflow port diameter of a hydrocyclone is the most important factor affecting Stage I underflow yield. As the underflow port diameter increased, the Stage I underflow yield also increased. Among the rest of the factors, the order of significance to Stage I underflow yield is, feed pressure followed by overflow pipe insertion depth, and the least significant factor is Stage I Inner overflow pipe diameter.

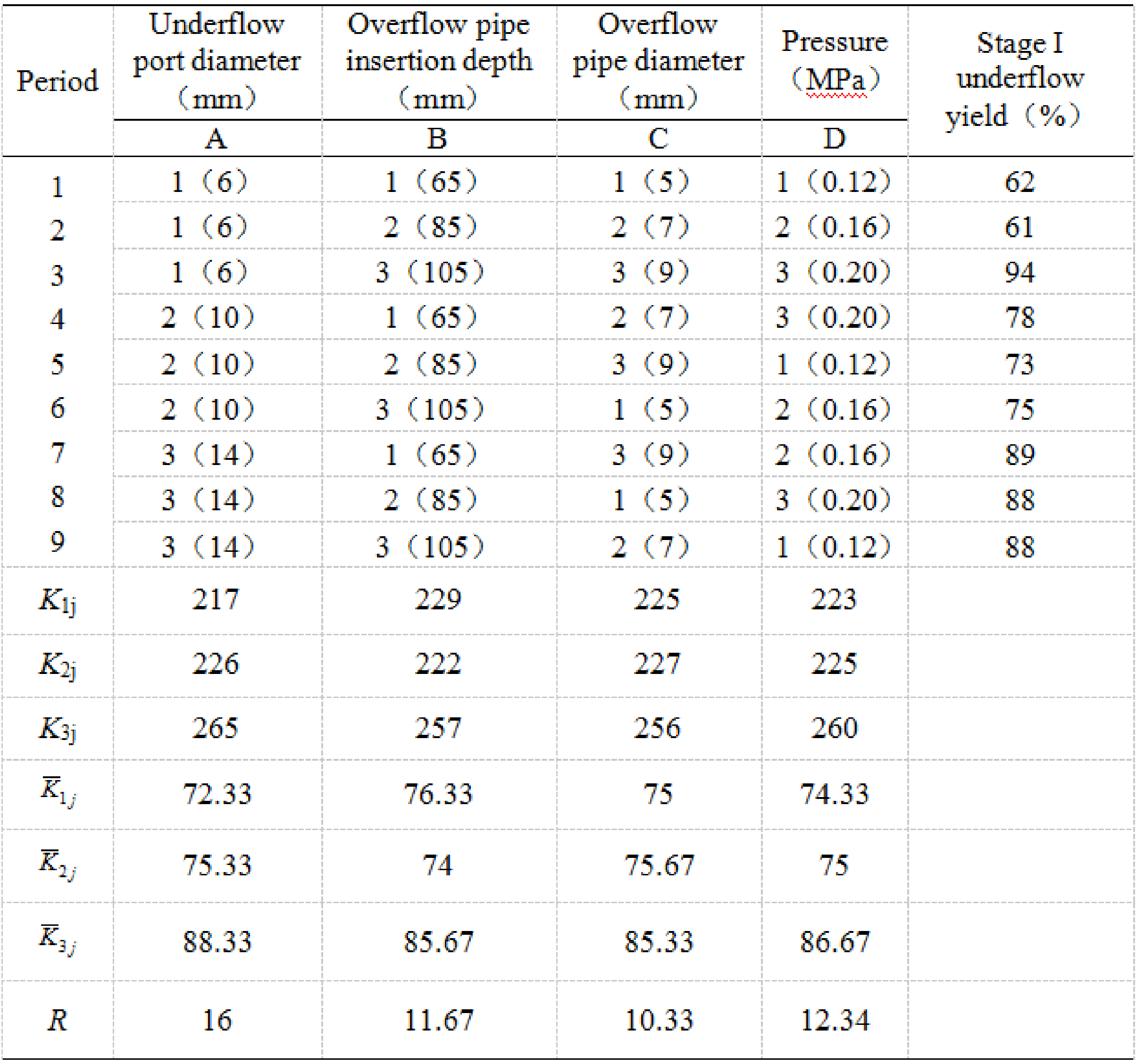


a b

c d

Fig. 11. The development of air column in the cyclone with diameter spigot a) 6 mm; b) 8 mm; c) 10 mm; d) 12 mm

Table 2. The orthogonal experiment of taking the first stage yield of spigot as assessment index.



Period	Underflow port diameter (mm)	Overflow pipe insertion depth (mm)	Overflow pipe diameter (mm)	Pressure (MPa)	Stage I underflow yield (%)
	A	B	C	D	
1	1 (6)	1 (65)	1 (5)	1 (0.12)	62
2	1 (6)	2 (85)	2 (7)	2 (0.16)	61
3	1 (6)	3 (105)	3 (9)	3 (0.20)	94
4	2 (10)	1 (65)	2 (7)	3 (0.20)	78
5	2 (10)	2 (85)	3 (9)	1 (0.12)	73
6	2 (10)	3 (105)	1 (5)	2 (0.16)	75
7	3 (14)	1 (65)	3 (9)	2 (0.16)	89
8	3 (14)	2 (85)	1 (5)	3 (0.20)	88
9	3 (14)	3 (105)	2 (7)	1 (0.12)	88
K_{1j}	217	229	225	223	
K_{2j}	226	222	227	225	
K_{3j}	265	257	256	260	
$\overline{K}_{1j}$	72.33	76.33	75	74.33	
$\overline{K}_{2j}$	75.33	74	75.67	75	
$\overline{K}_{3j}$	88.33	85.67	85.33	86.67	
R	16	11.67	10.33	12.34	

CONCLUSION

In the paper, A new multi-product cyclone was proposed to improve the separation precision and efficiency.The multi-product cyclone can obtain multiple products with different particle grading from one-step classification.

(1) The formation and evolution process of the air column inside cyclone with double vortex finders was conducted.

(2) In the orthogonal test, we deployed Stage I underflow yield as the evaluation indices, optimized and selected the best structure design and reasonable inlet pressure for the multi-product cyclone, and found the primary and secondary factors affecting the separation performance.

(3) Comprehensive analysis revealed that the underflow port diameter had the greatest impact on Stage I underflow yield, the Stage I inner overflow port diameter had no essential influence on Stage I underflow yield, neither the overflow pipe insertion depth nor the feed pressure is the key influential factor to Stage I underflow yield. To sum up, considering the impact of each factor, and energy consumption reduction for a multi-product cyclone, we confirmed the optimal structure parameters of the multi-product cyclone used in this paper: underflow port diameter 14mm, overflow pipe insertion depth 85mm, inner overflow pipe diameter 9mm, and feed pressure 0.16MPa.

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REFERENCES

1. A. Mainza, M. Narasimha, M.S. Powell, P.N. Holtham, M. Brennan. *J. Minerals Eng.*,**19**,1048 (2006).
2. K.T. Hsieh, K.Rajamani, *J. International Journal of Mineral Pro.,* **22**, 223 (1988).
3. S. Hore, S.K. Das, R. Singh, K.K. Bhattacharya, *J. International Journal of Coal Preparation and Utilization*, **32**(4), 193 (2012).
4. F. He, Y. Zhang, J. Wang, *J. Chem. Eng. Tech.*, **36**(11), 1935 (2013).
5. Y. Rama Murthy, K. Udaya Bhaskar, *J. Powder Tech.*, **230**, 36 (2012).
6. L. Svarovsky, Hydrocyclones, M. Holt, Rinehart and Winston, London, 1984.
7. Y. Xu, X. Song, Z. Sun, B. Tang, P. Li, J. Yu, *J. Ind. Eng. Chem. Res.*, **52**, 5470 (2013).
8. Hacifazliogluh, *J. International Journal of Coal Preparation and Utilization,* **32**(6), 290(2012).
9. K. Elsayed, C. Lacor, *J. Applied Mathematical Modelling,* **35**, 1952 (2011).
10. P.-K. Liu, L.-Y. Chu, J. Wang, Y.-F. Yu, *J. Chem. Engin. and Techno.*, **31**(3), 474 (2008).
11. M. Ghodrat, S.B. Kuang, A.B. Yu, A. Vince, G.D. Barnett, *J. Ind. Eng. Chem. Res.*, **52**, 16019 (2013).
12. Y.R. Murthy, K.U. Bhaskar, *J. Powder Technol.*, **230**, 36 (2012).
13. F.S. Kılavuz, Ö.Y. Gülsoy, *J. International Journal of Mineral Proces.,* **98**, 163 (2011).
14. Y. Xu, X. Song, Z. Sun, B. Tang, P. Li, J. Yu, *J. Ind. Eng. Chem. Res.*, **52**, 5470 (2013).
15. S.M. Mousavian,·A.F. Najafi, *J. Arch Appl Mech*, **79**, 395 (2009).
16. Z. Qi, S.B. Kuang, A.B. Yu. *J. International Journal of Min. Proces.*, **9**(142), 35 (2015).
17. R.K. Dwari, M.N. Biswas, B.C. Meikap, *J. Chem. Eng. Sci.*, **2**(59), 671 (2004).
18. D.P. Obeng, S. Morrell. *J. International Journal of Mineral Proces.,* **69**(3),129 (2003).
19. D.P. Obeng, S. Morrell, T.J. Napier-Munn, *J. International Journal of Mineral Proces.,* **76**(6), 181 (2005).
20. A. Mainza, M.S. Powell, B. Knopjes, *J. Minerals Engineering*, **17**(6), 573 (2004).
21. A. Mahmoud, M. Ibrahim, A. Galal, M.G. Farghaly, .*J. International Journal of Mineral Proces.,* **91**(4), 34 (2009).