Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 25(2015) 2422−2428
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Size dependent flow behaviors of particles in hydrocyclone based on multiphase simulation

Rui CUI[1], Guang-hui WANG [1], Mao-lin LI [2,3]

1. School of Chemical Engineering and Technology, Wuhan University of Science and Technology, Wuhan 430081, China;
2. Changsha Research Institute of Mining and Metallurgy Co., Ltd., Changsha 410012, China;
3. School of Resource and Environmental Engineering, Wuhan University of Science and Technology, Wuhan 430081, China

Received 22 September 2014; accepted 30 January 2015

Abstract: To investigate the flow behaviors of different size particles in hydrocyclone, a designed process was numerically simulated by the transient solver, where the quartz particles possessing a size distribution were injected into a 100 mm diameter hydrocyclone with the steady water field and air core inside. A lab experimental work has validated the chosen models in simulation by comparing the classification efficiency results. The simulated process shows that the 25 μm quartz particles, close to the cut size, need much more time than the finer and coarser particles to reach the steady flow rate on the outlets of hydrocyclone. For the particles in the inner swirl, with the quartz size increasing from 5 to 25 μm, the particles take more time to enter the vortex finder. The 25 μm quartz particles move outward in the radial direction when they go up to the vortex finder, which is contrary to the quartz particles of 5 μm and 15 μm as they are closely surrounding the air core. The studies reveal that the flow behaviors of particles inside the hydrocyclone depend on the particle size.
Key words: hydrocyclone; solid particles; flow behavior; computational fluid dynamics

1 Introduction

Hydrocyclone, characterized by its simplicity, high separation efficiency and throughput, has been widely used in the separation field of mineral processing and chemical industries. In spite of more than 100 years of application and much progress in the development of the design, studies on the hydrocyclone have not stopped due to the complicated flow field inside the hydrocyclone. In the past decades, researchers have taken great efforts to acquire the flow characteristics inside the hydrocyclone.

In 1952, KELSALL [1] used a optical microscope to determine the velocity of fine alumina powder inside a transparent hydrocyclone, and the results became the foundation for subsequent researches on hydrocyclone. Since then, techniques of laser Doppler anemometry (LDA) [2−4], and particle image velocimetry (PIV) [5,6] were used to measure the velocity profiles in hydrocyclone, and the typical velocity component distribution laws of the liquid flow were determined and acknowledged. However, compared with the flow behaviors of the liquid, the study of the flow behaviors of solid particles is more important to understand the separation principle, and to improve the separation efficiency. CHU and CHEN [7] measured the motion of solid particles inside a hydrocyclone using a particle dynamics analyser (PDA), and found that the axial velocity of some particles, which was thought to be equal to that of the water in the early literature, is not the same as that of the water. However, they did not discuss the velocities of particles with different sizes. And then, the techniques of tomography were reported to study the distribution of solid particles inside the hydrocyclone [8−10]. The work demonstrated the existence of radial and axial segregation of particles in the hydrocyclone through measuring the slurry density or concentration. The segregation implies that there were relative radial

Foundation item: Projects (2006BAB11B07, 2007BAB15B01) supported by the National Science & Technology Pillar Program during the Eleventh Five-year Plan Period, China; Project (2011BAB05B01) supported by the National Science & Technology Pillar Program during the Twelfth Five-year Plan Period, China
Corresponding author: Mao-lin LI; Tel: +86-13974851980; E-mail: limao-lin@vip.163.com
DOI: 10.1016/S1003-6326(15)63858-4

and axial movements between particles and liquid.

On the other hand, with the rapid development of computer and computational fluid dynamics (CFD) techniques, the parameters of both flow field and classification efficiency of particle sizes in hydrocyclone can be predicted [11−14]. In the work of BRENNAN et al [14], the particle segregation can be accurately predicted using the large eddy simulation (LES) technique for turbulence and the enhanced mixture model for granular phases. LIU et al [15] investigated the flow behaviors of 5, 15 and 30 μm sand particles inside a hydrocyclone using the Reynolds stress model (RSM) and Eulerian multiphase model. The results indicated that the tangential and axial velocities of the 30 μm particles have little decline, compared with that of the water phase.

Multiphase simulation is a good approach to study the flow behaviors of solid particles in hydrocyclone. However, for the prevailing multiphase models, there are some difficulties to reveal the flow parameters of solid particles. For example, the mixture model cannot directly obtain the velocities of the particles, and the complex Eulerian model is not easy to get convergent when the number of phases is too much. In this paper, in order to overcome the limitations of the multiphase models and investigate the flow behaviors of different size particles inside a hydrocyclone, the transient simulation of a hypothetical scene with RSM turbulent model and mixture multiphase model was carried out in Ansys Fluent software. And the laboratorial classification experiment was conducted to verify the simulated results.

2 Experimental

The quartz powder with a density of 2660 kg/m^3 was used in the classification tests. The particle size distribution was determined by the combination of sieving and sedimentation method. The results are shown in Table 1.

The laboratory experimental apparatus is shown in Fig. 1. The inlet and outlet of the centrifugal pump are connected to the slurry tank and the hydrocyclone, respectively. The rotating speed of the pump is controlled by a frequency converter. A by-pass pipeline is set to slurry circulation and feed sampling. During the tests, the mass fraction of quartz powder of feed slurry was about 20% and the feeding pressure gauge was controlled at 0.08 MPa, which meant that the inlet velocity was about 4.1 m/s. After the pressure was stable, samples of overflow and underflow products were collected simultaneously in different containers. Then, the collected underflow and overflow products were filtered, dried and weighed. The particle size distributions of the representative samples of the dried products were also analyzed.

Table 1 Particle size distribution of feed

Size/μm	Fraction/%	Passing/%
>45	20.10	100.00
38−45	7.73	79.89
30−38	9.48	72.16
20−30	19.59	62.68
10−20	29.48	43.09
<10	13.61	13.61

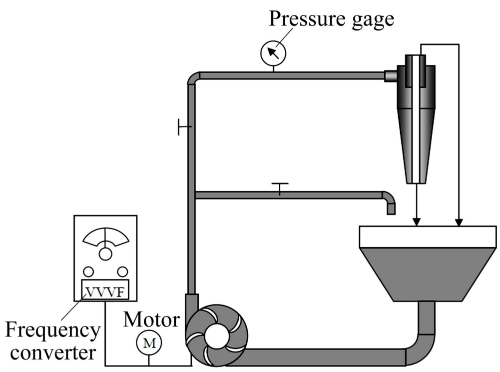

Fig.1 Schematic diagram of laboratory experimental apparatus

3 Simulation

3.1 Geometry and mesh

The geometry of the lab hydrocyclone with a diameter of 100 mm and a single cone angle of 10° used for simulation is shown in Fig. 2, in which the sectional

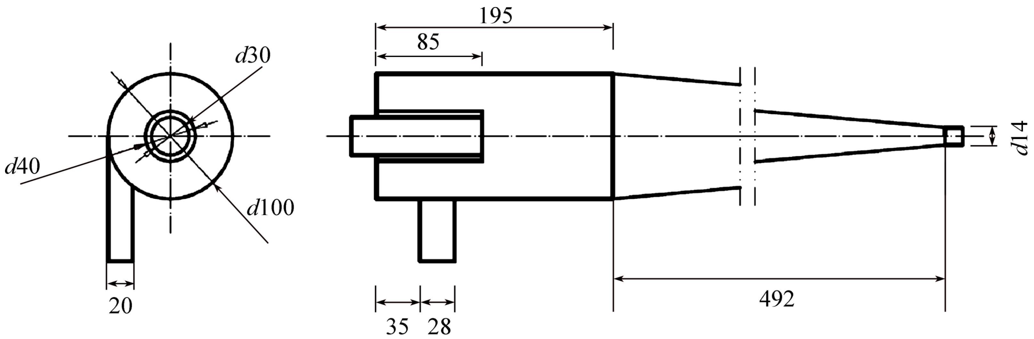

Fig. 2 Hydrocyclone geometry (Unit: mm)

view of the chamber is also depicted with main dimensions. Figure 3 shows the isometric view of the 3D body fitted grid generated by the ICEM CFD software. The number of the computational cells is about 427000.

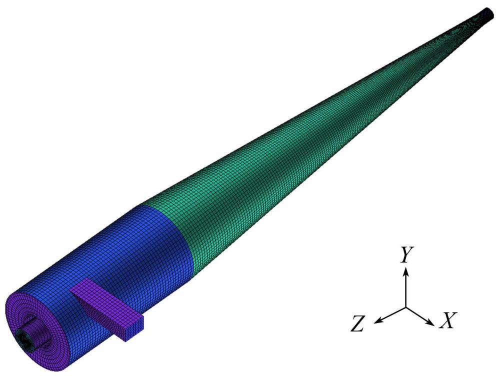

Fig. 3 Grid of hydrocyclone

3.2 Simulation strategy and settings

This work directly focuses on the simulation strategy and settings rather than describing the transport equations, because some Refs. [14,16,17] have reported the theoretical description of RSM and mixture model in details. The rectangular feed inlet was designated as the velocity inlet with the value of 4.1 m/s. Both outlets were designated as the pressure outlets, which allow the backflow into the outlets of hydrocyclone. The backflow direction was specified as normal to the boundary of outlets and the backflow turbulence intensity was set to 5%. The operating pressure and gravity were set to 101.325 kPa and 9.81 m/s^2, respectively, with the direction along the negative *Z* coordinate axis.

In this simulation, the following three steps were conducted to obtain the final results.

1) The case was initialized with the hydrocyclone full of water. The steady simulation was performed with the RSM model until the reversed flow on the outlets was reported by the Ansys Fluent.

2) The transient solver and the volume of fluid (VOF) multiphase model were then enabled, and the backflow volume fraction of air on the pressure outlets was set to 1. The calculation was run until the air core was formed and the mass flow rate of water achieved balance.

3) The mixture model with the granular option for particles was then enabled, using six quartz phases, water and air in the multiphase simulation. The diameters of the granular phases with density of 2660 kg/m^3 were set to 5, 15, 25, 34, 41.5 and 50 μm, and the volume fraction of each quartz size in the feed inlet was set to 0.011, 0.025, 0.016, 0.008, 0.006 and 0.017, respectively. Noting that the slip velocity of air to water was set to zero, which means that there is no interpenetration between the water and the air. The mass flow rates of water and granular phases were recorded at 0.2 s interval during the whole simulation.

4 Results and discussion

4.1 Validation results

The mass flow rates of water and quartz phases on the outlets of hydrocyclone, calculated by averaging the recorded instantaneous values from 16.06 to 22.66 s, are listed in Table 2. The mass flow rate of each phase in feed was obtained by adding the averaged values in underflow and overflow together.

According to the data in Table 2, the product indices such as concentration and yield can be calculated. Table 3 lists the product indices derived from simulation and experiment.

Table 2 Mass flow rates of water and granular phases ($10^{-3}kg \cdot s^{-1}$)

Product	Water	Granular phases					
		5 μm	15 μm	25 μm	34 μm	41.5 μm	50 μm
Overflow	2008.1	64.23	134.7	57.57	1.289	0.1362	0.04515
Underflow	96.06	3.420	15.83	43.52	42.69	35.82	99.61
Feed	2104.2	67.65	150.6	101.1	43.98	35.95	99.66

Table 3 Comparison of product indices obtained from simulation and lab test (mass fraction, %)

Product	Simulated		Experimental	
	Concentration	Yield	Concentration	Yield
Overflow	11.39	51.72	12.08	52.89
Underflow	71.49	48.28	65.48	47.11
Feed	19.17	100.00	19.62	100.00

Table 3 shows that the feed concentration calculated by the simulated data is similar with the concentration in laboratorial test. It is indicated that the simulation reaches the steady flow and the overall material balance is achieved, although the underflow concentration is over predicted by about 6%. This over prediction would be ascribed to the over prediction of the density in the near wall region where the lift forces are ignored [17]. Although the results can be improved by modeling the lift forces [16], the deviation will not qualitatively affect the overall flow behaviors of solid particles.

Figure 4 shows the curves of predicted and experimental separation efficiency, in which the fraction of each quartz size reporting to the underflow is plotted. The separation efficiency of simulation is in well agreement with that of lab test. This indicates that the acceptable predicted classification results can be obtained using the RSM turbulence model and the mixture multiphase model.

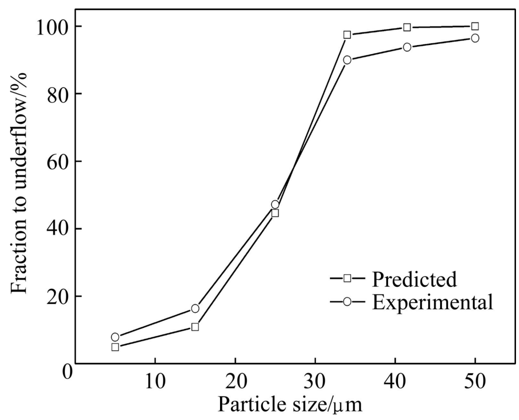

Fig. 4 Curves of separation efficiency

4.2 Flow behavior of particles

The instantaneous mass flow rate of each quartz size on the outlets of hydrocyclone, reported during the transient iteration of simulation, is a function of time. Figure 5 shows the instantaneous mass flow rates plots of six kinds of quartz size, starting at the time when the quartz phases are introduced into the hydrocyclone.

These plots indicate that the time the quartz particles needs to achieve the time averaged steady mass flow rates on the overflow and underflow is significantly different. It means that the flow behavior of particle inside the hydrocyclone is clearly influenced by the particle size. It is obviously shown that the 25 μm quartz particles need more time to achieve the mass balance,

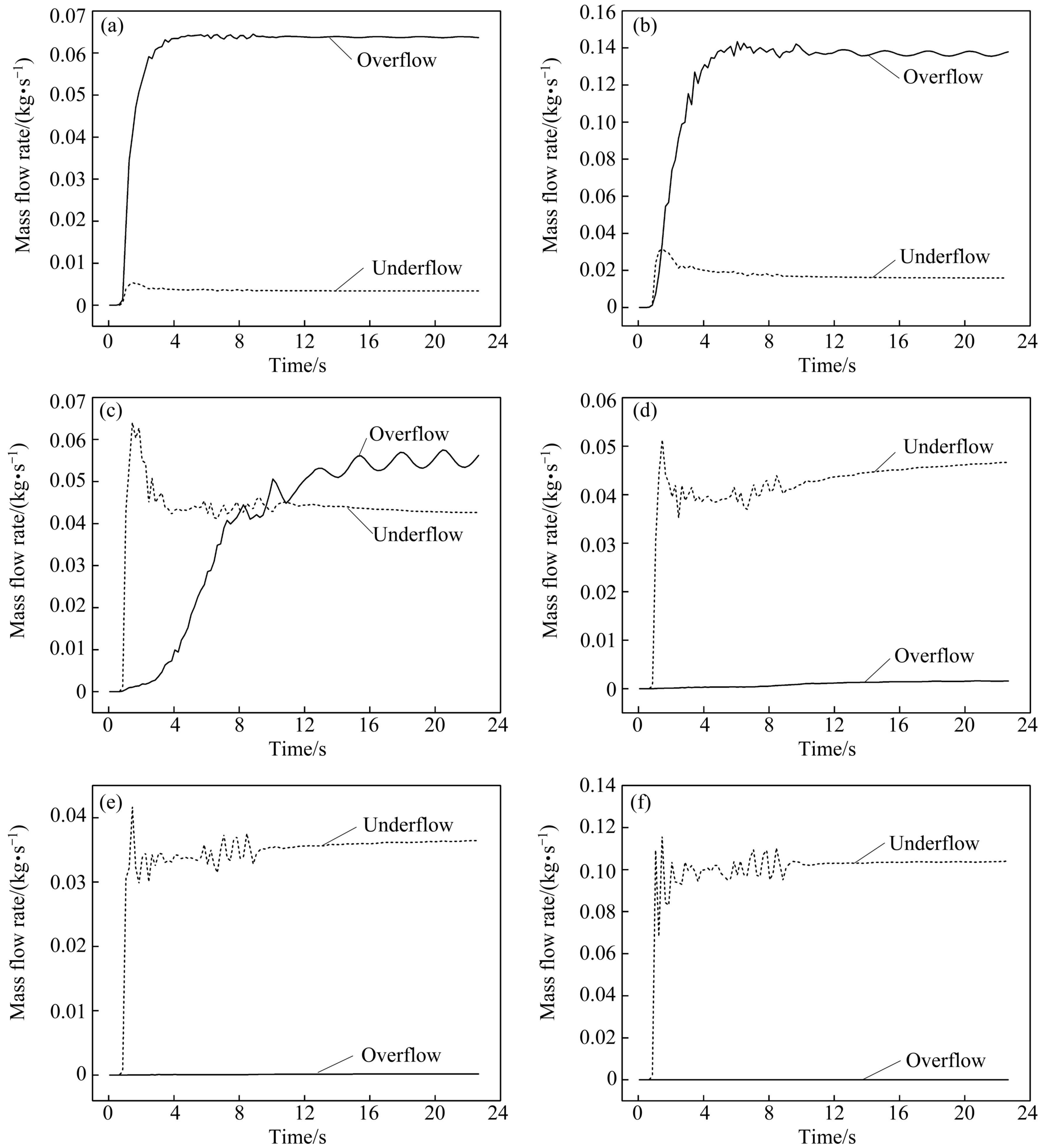

Fig. 5 Instantaneous mass flow rate of each quartz size on outlets of hydrocyclone: (a) 5 μm; (b) 15 μm; (c) 25 μm; (d) 34 μm; (e) 41.5 μm; (f) 50 μm

compared with the finer particles and the coarser particles. That is to say, the 25 μm quartz particles have a relatively longer residence time inside the hydrocylone. This may be because that the value of 25 μm is close to the cut size (as shown in Fig. 4), which has an equal chance of reporting to either the underflow or the overflow and is shown to be very unstable [18].

Secondly, before reaching the steady flow, there are different growth rates of mass flow rate on the overflow for different quartz sizes. As shown in Fig. 6, it is clear that the slope of mass flow curve declines, following the increase of particle size. It means that the mass flow rate of fine quartz particles reporting to the overflow increases faster than that of coarse particles. Since the particles flowing into the overflow are mainly derived from the inner upward swirl, a conclusion could be deduced that the flow behaviors of different particle sizes have discrepancy in the inner swirl.

Figure 7 shows the contours of instantaneous volume fraction for three kinds of quartz size inside the hydrocyclone in X=0 plane. Note that the central purple region in each instantaneous plot is the corresponding moment air core, and the contours in these plots are plotted on the same logarithmic scale color map.

As shown in Fig. 7, in the instantaneous plots of 0.74 s, the quartz particles of 5, 15 and 25 μm in the region of about 275 mm below the Z=0 plane, have

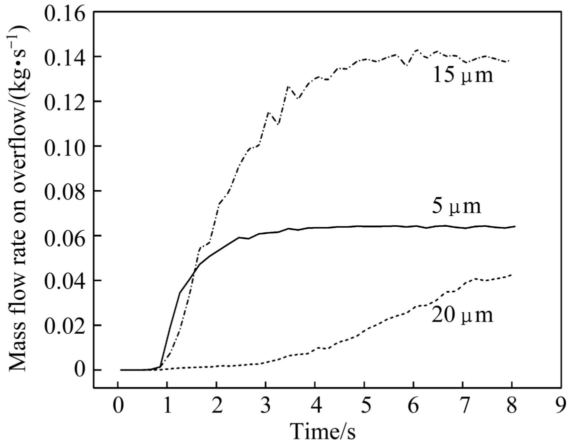

Fig. 6 Instantaneous mass flow rate of three quartz size to overflow

moved close to the air core. This indicates that the quartz particles start to migrate from the outer swirl to the inner swirl, and the axial velocity direction of particles will reverse in the following time. After 0.08 s, a visible difference can be found that the finer quartz particles move up further during the same time interval, among the sizes of 5, 15 and 25 μm. This may be attributed to the momentum of particle. Due to the less momentum, the fine particles tend to follow water more easily than the coarse particles. In other words, the coarse particles

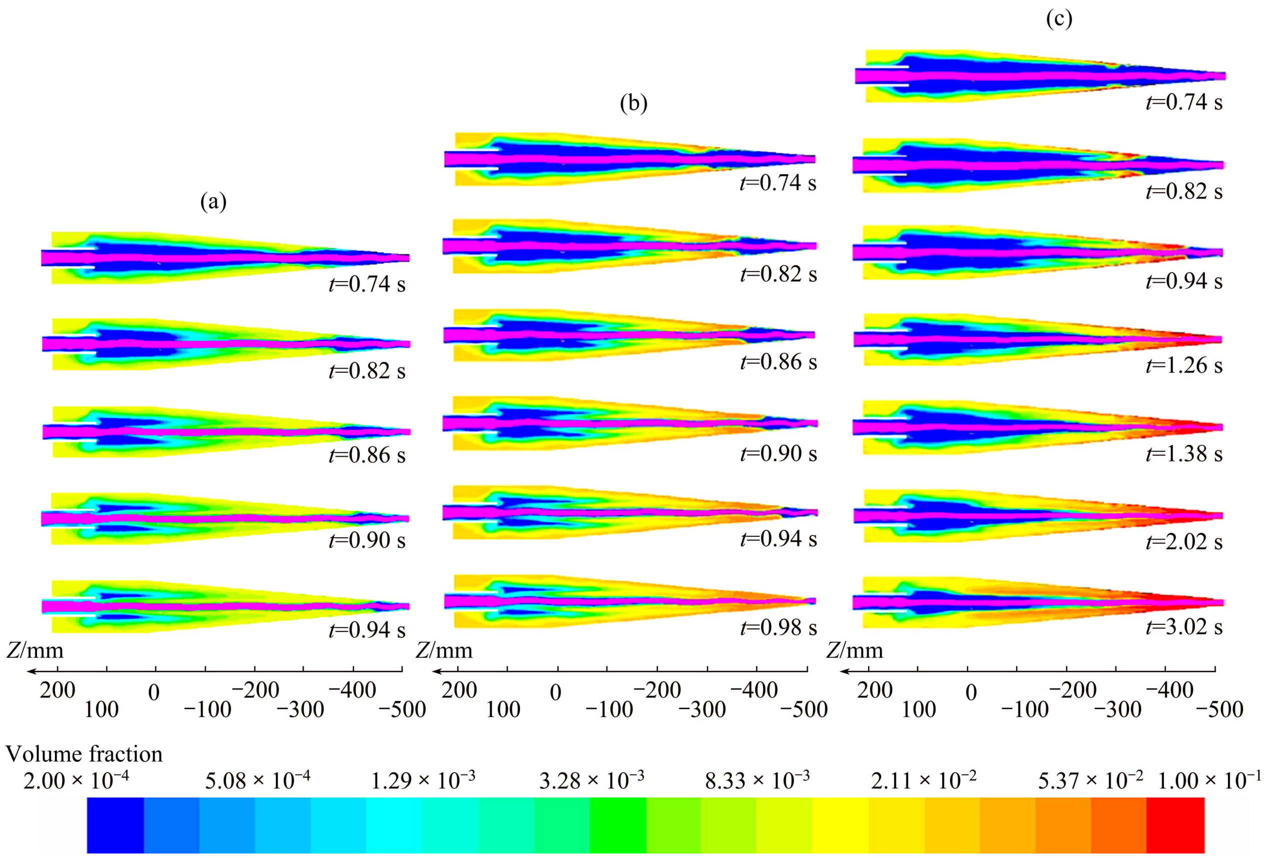

Fig. 7 Contours of instantaneous volume fraction inside hydrocyclone in X=0 plane: (a) 5 μm; (b) 15 μm; (c) 25 μm

take more time to reverse the motion direction and to accelerate to the same velocity value. Consequently, the coarse particles appear to be falling behind the fine particles. As shown in Fig. 7, with increasing the quartz size, the upward particle stream needs more time to enter into the vortex finder. Figure 7 also shows that the residence time of 5, 15 and 25 μm quartz particles inside the hydrocyclone is less than 0.9 s, more than 0.94 s and about 3 s, respectively.

Besides that, for the 5 and 15 μm quartz particles, a common flow characteristic of the rising inner swirl is that the particle stream closely surrounds the air core, so that a blank region without particles forms between the outer and inner swirls at the initial stage. On the contrary, the 25 μm quartz stream flows away from the air core during the upward movement, which may be mainly caused by the higher centrifugal force. This flow behavior may lead to the radial migration of particles from the inner swirl to the outer swirl, and form a circular flow.

In addition, the distinct short circuit flow of quartz can also be captured in Fig. 7. It can be seen that the short circuit flow occurs by descending the movement of the quartz flow along the outer wall of vortex finder. However, it is not at the same time that the short circuit flow occurs. When the quartz size is 25 μm, the occurrence of short circuiting appears to be significantly late.

5 Conclusions

1) The simulation of the quartz particles in a hydrocyclone suggests that the 25 μm quartz particles, close to the cut size, need much more time to reach the steady mass flow rate on the outlets of hydrocyclone.

2) For those particles reporting to the overflow from the inner swirl, the flow behaviors depend on the particle size according to the speed and direction of the ascending particle stream.

3) As the quartz size increases from 5 to 25 μm, the upward particle stream needs more time to enter into the vortex finder.

4) The 25 μm quartz particles move towards the wall of hydrocylone, contrary to the quartz particles of 5 μm and 15 μm that are closely surrounding the air core. Apart from this, when the quartz size is 25 μm, the occurrence of short circuit flow appears to be significantly later than that of the 5 μm and 15 μm quartz particles.

References

[1] KELSALL D F. A study of the motion of solid particles in a hydraulic cyclone [R]. Berks: Atomic Energy Research Establishment, 1952.

[2] DABIR B, PETTY C A. Measurements of mean velocity profiles in a hydrocyclone using laser Doppler anemometry [J]. Chemical Engineering Communications, 1986, 48(4−6): 377−388.

[3] HSIEH K T, RAJAMANI K. Phenomenological model of the hydrocyclone: Model development and verification for single-phase flow [J]. International Journal of Mineral Processing, 1988, 22(1): 223−237.

[4] MARINS L P M, DUARTE D G, LOUREIRO J B R, MORAES C A C, SILVA FREIRE A P. LDA and PIV characterization of the flow in a hydrocyclone without an air-core [J]. Journal of Petroleum Science and Engineering, 2010, 70(3): 168−176.

[5] ZHANG Dan, CHEN Ye. Effect of the cone angle on flow field and separation performance of solid-liquid hydrocyclone [J]. Fluid Machinery, 2009, 37(8): 11−16. (in Chinese)

[6] CUI Bao-yu, WEI De-zhou, GAO Shu-ling, LIU Wen-gang, FENG Yu-qing. Numerical and experimental studies of flow field in hydrocyclone with air core [J]. Transactions of Nonferrous Metals Society of China, 2014, 24(8): 2642−2649.

[7] CHU Liang-yin, CHEN Wen-mei. Research on the motion of solid particles in a hydrocyclone [J]. Separation Science and Technology, 1993, 28(10): 1875−1886.

[8] GALVIN K P, SMITHAM J B. Use of X-rays to determine the distribution of particles in an operating cyclone [J]. Minerals Engineering, 1994, 7(10): 1269−1280.

[9] WILLIAMS R A, JIA X, WEST R M, WANG M, CULLIVAN J C, BOND J, FAULKS I, DYAKOWSKI T, WANG S J, CLIMPSON N, KOSTUCH J A, PAYTON D. Industrial monitoring of hydrocyclone operation using electrical resistance tomography [J]. Minerals Engineering, 1999, 12(10): 1245−1252.

[10] SUBRAMANIAN V S. Measuring medium segregation in the dense-medium cyclone using gamma-ray tomography [D]. Brisbane: Julius Kruttschnitt Mineral Research Centre, University of Queensland, 2002.

[11] GAO Shu-ling, WEI De-zhou, LIU Wen-gang, MA Long-qiu, LU Tao, ZHANG RUI-yang. CFD numerical simulation of flow velocity characteristics of hydrocyclone [J]. Transactions of Nonferrous Metals Society of China, 2011, 21(12): 2783−2789.

[12] MURTHY Y R, BHASKAR K U. Parametric CFD studies on hydrocyclone [J]. Powder Technology, 2012, 230: 36−47.

[13] CUI Bao-yu, WEI De-zhou, DI Qing-xiang, ZHANG Si-yao. Numerical study on flow field inside a hydrocyclone [J]. Journal of Northeastern University, 2014, 35(6): 894−897. (in Chinese)

[14] BRENNAN M S, NARASIMHA M, HOLTHAM P N. Multiphase modelling of hydrocyclones–prediction of cut-size [J]. Minerals Engineering, 2007, 20(4): 395−406.

[15] LIU Xin-yang, LUO Jin-yao, GAO Chuan-chang. 3D numerical simulation of water and sediment two-phase flow in a hydrocyclone [J]. Journal of Hydroelectric Engineering, 2010(4): 224−229. (in Chinese)

[16] NARASIMHA M, BRENNAN M S, HOLTHAM P N. CFD modeling of hydrocyclones: Prediction of particle size segregation [J]. Minerals Engineering, 2012, 39: 173−183.

[17] NARASIMHA M, BRENNAN M S, HOLTHAM P N. Numerical simulation of magnetite segregation in a dense medium cyclone [J]. Minerals Engineering, 2006, 19(10): 1034−1047.

[18] WANG B, CHU K W, YU A B. Numerical study of particle-fluid flow in hydrocyclone [J]. Industrial & Engineering Chemistry Research, 2007, 46(13): 4695−4705.

基于多相流模拟的水力旋流器内依赖于粒度的颗粒流动行为

崔 瑞[1] 王光辉[1] 李茂林[2,3]

1. 武汉科技大学 化学工程与技术学院，武汉 430081；
2. 长沙矿冶研究院有限责任公司，长沙 410012；
3. 武汉科技大学 资源与环境工程学院，武汉 430081

摘 要：为研究水力旋流器内不同粒度颗粒的流动行为，设计了这样一个过程：将具有一定粒度分布的颗粒群注入一个具有稳定流场与空气柱的直径为 100 mm 的水力旋流器中，并通过瞬态求解器来模拟这一过程。通过比较分级效率结果，用实验验证了数值模拟所选择的数值模型。模拟过程表明：相比于粗颗粒与细颗粒，接近分离粒度的 25 μm 石英颗粒需要消耗更多的时间在旋流器的出口形成稳定的质量流率。随着粒度从 5 μm 增加到 25 μm，处于内旋流中的颗粒需要更多的时间才能进入溢流管。25 μm 石英颗粒在上升至溢流管的过程中在径向上朝外运动，这与 5 μm 和 15 μm 石英颗粒向上运动时紧紧包围空气柱的现象刚好相反。研究结果表明：颗粒在旋流器内的流动行为是依赖于颗粒粒度的。

关键词：水力旋流器；固体颗粒；流动行为；计算流体力学

(Edited by Mu-lan QIN)