Available online at www.sciencedirect.com

ScienceDirect

Trans. Nonferrous Met. Soc. China 21(2011) 2783−2789

Transactions of Nonferrous Metals Society of China

www.tnmsc.cn

CFD numerical simulation of flow velocity characteristics of hydrocyclone

GAO Shu-ling, WEI De-zhou, LIU Wen-gang, MA Long-qiu, LU Tao, ZHANG Rui-yang

College of Resources and Civil Engineering, Northeastern University, Shenyang 110004, China

Received 8 April 2011; accepted 8 October 2011

Abstract: A CFD based numerical simulation of flow velocity of hydrocyclone was conducted with different structural and operational parameters to investigate its distribution characteristics and influencing mechanism. The results show there exist several unsymmetrical envelopes of equal vertical velocities in both upward inner flows and downward outer flows in the hydrocyclone, and the cone angle and apex diameter have remarkable influence on the vertical location of the cone bottom of the envelope of zero vertical velocity. It is also found that the tangential velocity isolines exist in the horizontal planes located in the effective separation region of hydrocyclone. The increase of feed pressure has almost no effect on the distribution characteristics of both vertical velocity and tangential velocity in hydrocyclone, but the magnitude and gradient of tangential velocity are increased obviously to make the motion velocity of high density particles to the wall increased and to make the cyclonic separation effect improved.

Key words: numerical simulation; hydrocyclone; flow velocity characteristics; structural parameter; operational parameter; cyclonic separation effect

1 Introduction

Hydrocyclone is a classical equipment utilizing compound field of centrifugal force and gravity. It is applied to series of separating processes such as solid−solid [1], solid−liquid [2], liquid−liquid [3], solid−gas [4], which are treated frequently in many industrial fields such as mining, chemistry, petrol, biology, medicine. The studies with regard to its separation characteristics are usually carried out by experimental methods, and are investigated by changing the structural and operational parameters accordingly [5]. Actually, the motion behaviors of particles in the hydrocyclone depend on the flow field, and it is by the means of changing the flow characteristics in the hydrocyclone that these parameters influence the motion behaviors of solid particles and their separation results. Therefore, the flow characteristics of the hydrocyclone are the key points which decide the actual separation result of particles.

With the developments of computer technology and numerical arithmetic, numerical simulation becomes a forceful approach to scientific research in recent years, as well as theory study and experimental research. The numerical simulation of flow field utilizing the method of computational fluid dynamics (CFD) have been accepted broadly, which have also been adopted successfully in classification [6], thickening [7], dense medium separation [8−9], jigging concentration [10], flotation [11−12] and other minerals processing technologies. The numerical simulation based on CFD has become an effective approach to investigate the dynamical characteristics of flow and particles, which have been validated to accord with the experimental data nearly [13−14].

However, the numerical simulations on flow field of dense medium and hydrocyclone were almost conducted in some fixed structural and operational conditions, while how these parameters influence the flow field has not been investigated clearly. Therefore, the flow velocities in hydrocyclone were simulated systematically with different structural and operational parameters in the present study, so as to investigate the velocity characteristics and the influencing mechanism.

2 Experimental

2.1 Model of numerical simulation

FLUENT is a kind of popular and commercial software based on the computational fluid dynamics

Foundation item: Project (50974033) supported by the National Natural Science Foundation of China; Project (N100301002) supported by the Fundamental Research Funds for the Universities, China

Corresponding author: GAO Shu-ling; Tel/Fax: +86-24-83692711; E-mail: gaoshuling@mail.neu.edu.cn

DOI: 10.1016/S1003-6326(11)61124-2

(CFD) and it provides lots of turbulent models. It has been reported that k—ε model can usually obtain more according simulation results, so it was chosen to perform the simulation.

2.2 Boundary conditions and structural parameters

The boundary conditions are set as follows:

1) Velocity inlet is set at the flow velocity magnitude measured;

2) Pressure outlet is set at zero, which is expressed with relative pressure;

3) The no slipping boundary condition is put on all walls, where every velocity component is zero.

All the structural parameters used in the simulation are listed in Table 1.

Table 1 Structural parameters used in simulation

Structural parameter	Value
Diameter of hydrocyclone/mm	75
Diameter of feed inlet/mm	13
Diameter of overflow pipe/mm	17
Depth of overflow pipe/mm	69.6
Height of cylindrical section/mm	84.5
Height of conical section/mm	508(7°), 288(11°), 202(15°), 166(19°)
Diameter of apex/mm	6, 10, 16

2.3 Simulation procedure

The simulations were conducted using computational fluid dynamic code Fluent 6.3, which includes pre-processing (Gambit) and solving (Fluent). Physical geometry, mesh generating and boundary conditions were treated through Gambit. Furthermore, Fluent was used to perform computation and analyses. The computational mesh was generated with hexahedron and tetrahedron, accordingly, and the four hydrocyclones with cone angle of 7°, 11°,15° and 19° were split to 63394, 57955, 55162 and 54721 grids, respectively.

3 Results and discussion

3.1 Vertical velocity characteristics

3.1.1 Distribution of vertical velocity with different structural parameters

The distributions of vertical velocity in hydrocyclone with different apex diameters and cone angles are shown in Fig. 1.

It can be found clearly from Fig. 1 that upward inner flows appear in the whole region of cylindrical and conical sections. In the inner flows there exist several envelopes of equal vertical velocity. The shapes of these

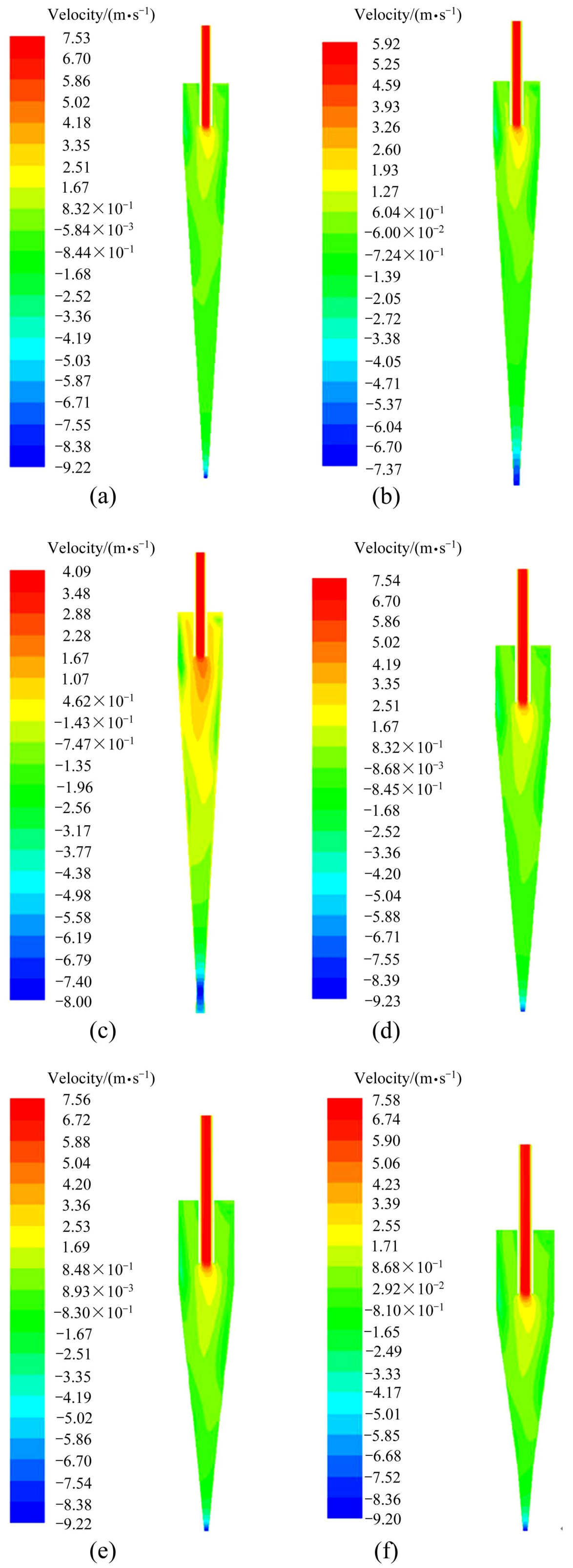


Fig. 1 Distribution of vertical velocity with different structural parameters: (a) Cone angle of 7°, apex diameter of 6 mm; (b) Cone angle of 7°, apex diameter of 10 mm; (c) Cone angle of 7°, apex diameter of 16 mm; (d) Cone angle of 11°, apex diameter of 6 mm; (e) Cone angle of 15°, apex diameter of 6 mm; (f) Cone angle of 19°, apex diameter of 6 mm

envelopes seem like the hydrocyclone to a certain extent, but they are not symmetrical actually. Furthermore, the closer the envelope to the overflow pipe is, the higher the vertical velocity is. In another aspect, the spacial locality where the envelope of zero vertical velocity (it is also called LZVV) reaches the lowest point (it is also named cone bottom of LZVV) in the conical section moves upward along the vertical axis with the increase of apex diameter, by which the experimental phenomenon [15] that the flow ratio of overflow reduces with the enlarging of apex diameter could be explained logically. In the meantime, it also shows the reduction of effective separation regions so that particles could pass promptly through LZVV and then cannot be separated any more. In the outside of LZVV where are occupied by outer flows, the closer the distance to the bottom of the conical is, the higher the vertical velocity is. However, the region of outer flows does not have any separation function to particles, it works merely as an exit of underflow. In addition, the vertical velocity in the whole region decreases when the diameter of apex is increased. While the size of LZVV changes accordingly when the cone angle is increased.

3.1.2 Changing trends of centerline vertical velocity with different structural parameters

For the sake of investigating the detailed locality of cone bottom of LZVV and the numerical changing trend of vertical velocity, the centerline vertical velocity with different apex diameters and cone angles were simulated respectively, which are shown in Fig. 2.

It can be seen from Fig. 2 that the flow vertical velocity is downward in the conical section downside, in which the velocity increases more rapidly when the locality is closer to the apex (except when the cone angel is 7° and the diameter of apex is 16 mm, the flow vertical velocity decreases in the apex region because the diameter of apex top is 12 mm). It could also be found that the flow velocity increases more slowly with the rising of the height of conical section and turns to upward gradually. The upward flow velocity also increases in little with it, but increases in an extremely rapid degree at the interface of cylindrical section and conical section, then keeps at a relatively high velocity steadily in the overflow pipe.

Generally speaking, when the cone angle is fixed, the larger the apex diameter is, the lower the flow vertical velocity is. The trends described above are obvious in the conical section downside and the overflow pipe section. The velocities at the three different apex diameters are similar at the same height in the inside region of LZVV, which is usually considered the effective separation region in hydrocyclone. However, the similar degrees of the three velocities are distinct slightly when the cone angles are different, which shows

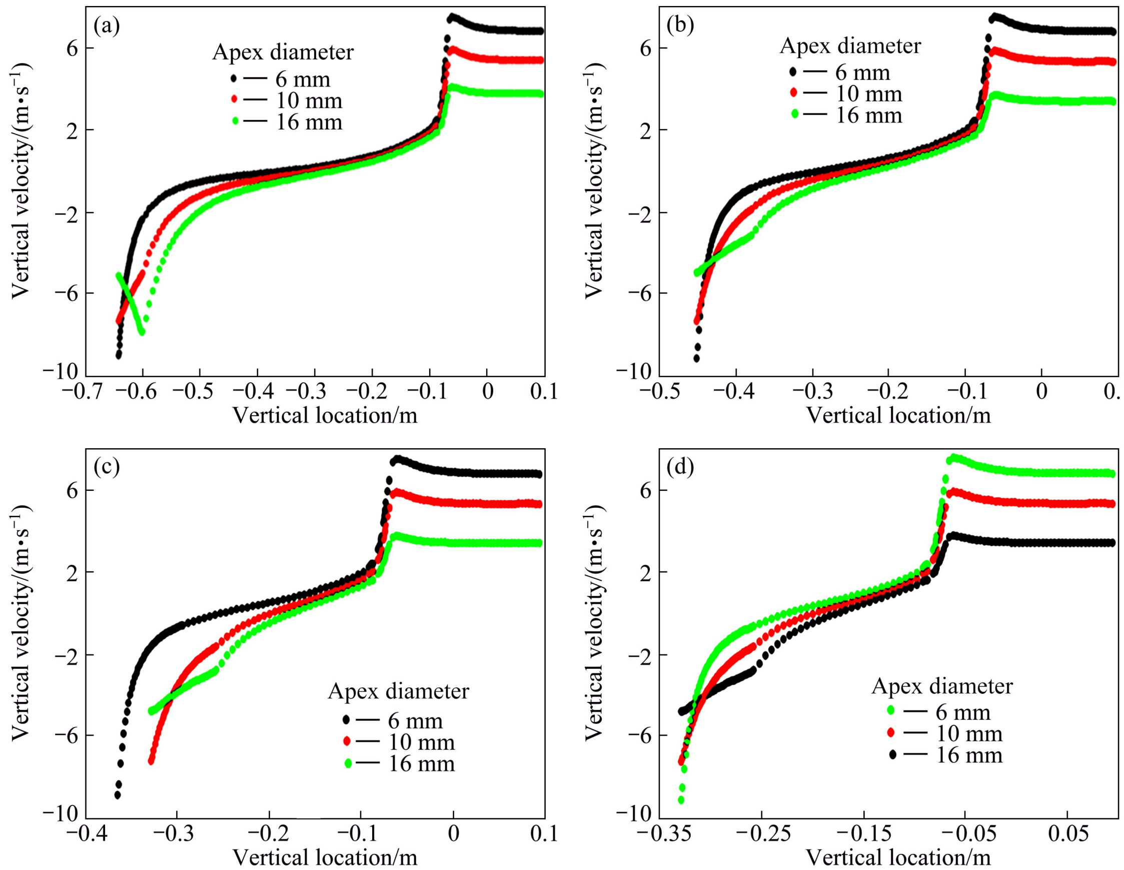


Fig. 2 Changing trends of centerline vertical velocity with different structural parameters: (a) 7°; (b) 11°; (c) 15°; (d) 19°

that the smaller the cone angle is, the more similar the three velocities are. According to the analysis above, it can be inferred that the smaller the cone angle is, the less the influence of apex diameter on the flow velocity is, and the more unobvious the effect of apex diameter on the improvement of separation results, which accord well with the results of beneficiation of diasporic bauxite by hydrocyclone [16].

The detailed vertical locations of the cone bottom of LZVV with different structural parameters are listed in Table 2, by which its changing trends are judged to be distinct.

Table 2 Vertical location of cone bottom of LZVV with different structural parameters

Cone angle/(°)	Vertical location/m		
	Apex diameter 6 mm	Apex diameter 10 mm	Apex diameter 16 mm
7	−0.36	−0.29	−0.24
11	−0.30	−0.26	−0.22
15	−0.25	−0.20	−0.17
19	−0.23	−0.20	−0.17

3.1.3 Vertical velocity characteristics with different feed pressures

The distributions of vertical velocity and the changing trends of centerline vertical velocity with different feed pressures are shown in Fig. 3 and Fig. 4 respectively. It should be mentioned that the numerical simulation is carried out with the same structural parameters that the cone angle is 11° and the apex diameter is 6 mm.

It can be found obviously from Fig. 3 that the flow vertical velocity rises with the increase of feed pressure. However, the distribution characteristics of the envelopes of equal vertical velocity, including the spacial locality, shape, and region size, do not change with it at all. Therefore, it can be inferred that feed pressure almost has no effect on the distribution characteristics of vertical velocities in the hydrocyclone.

It can be seen from Fig. 4 that the changing trends of centerline vertical velocity with the rising of vertical height are just the situation described above. It can be also found further that the vertical locations of the cone bottom of LZVV with different feed pressures are at the same point. These characteristics show this operating parameter has no remarkable influence on the location and region size of LZVV. Therefore, once the structural parameters are fixed, the split ratio of inner flow to outer flow is determined, as well as the ratio of overflow to underflow.

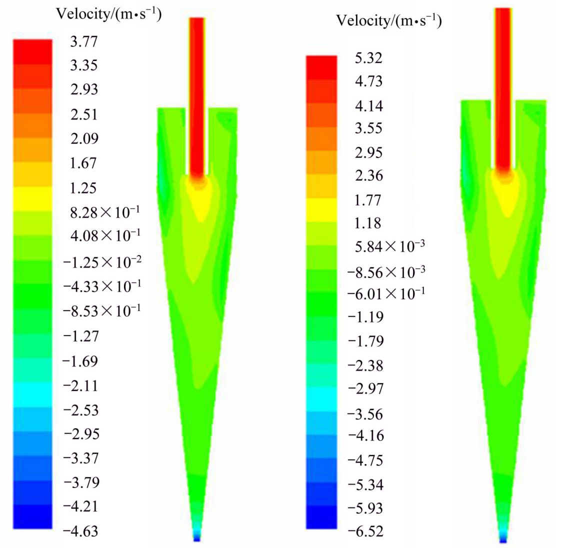


Fig. 3 Distributions of vertical velocity with different feed pressures: (a) 0.1 MPa; (b) 0.2 MPa; (c) 0.3 MPa; (d) 0.4 MPa

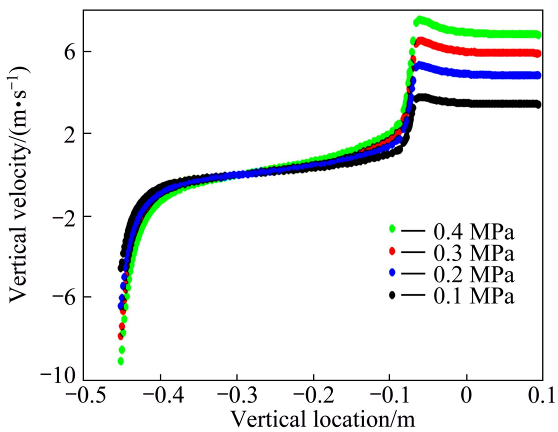
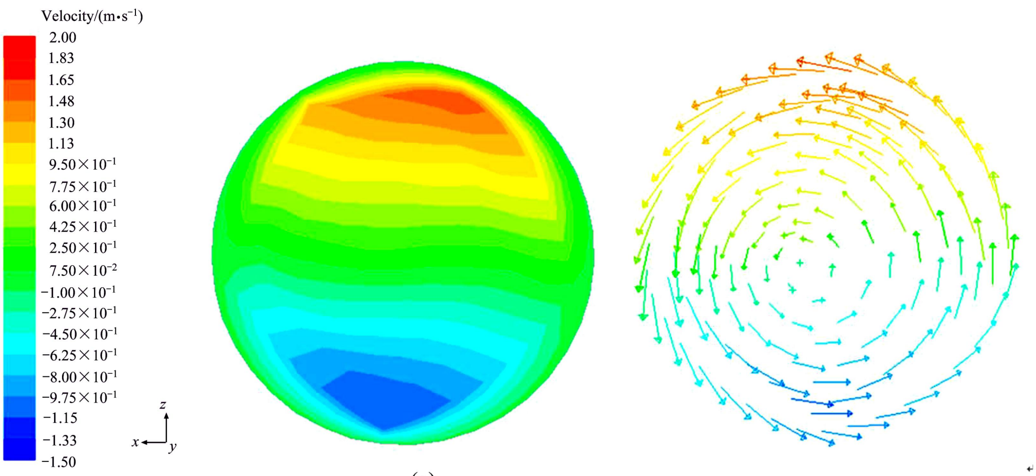


Fig. 4 Changing trends of centerline vertical velocity with different feed pressures

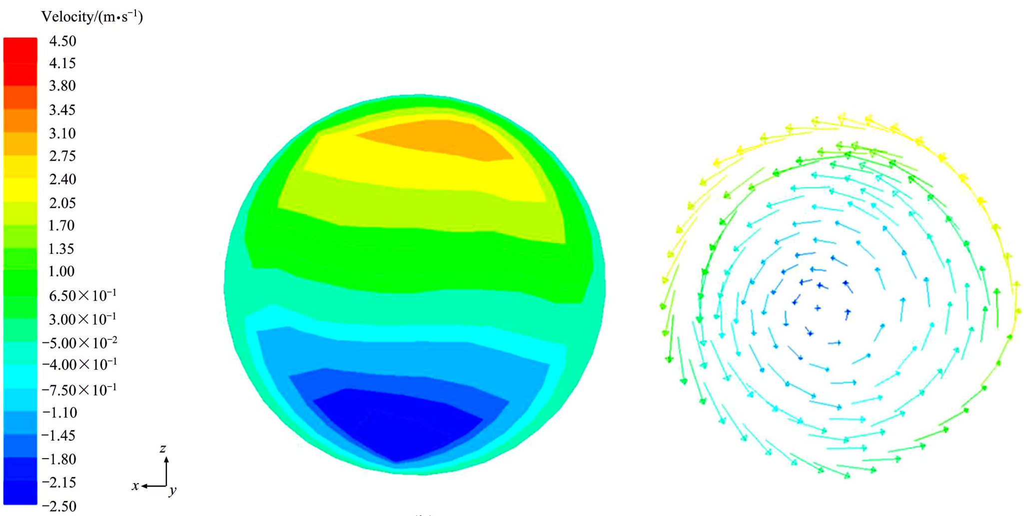
3.2 Tangential velocity characteristics

For the sake of investigating the influence of feed pressure on the flow velocity and mineral separation mechanism in hydrocyclone further, the tangential velocity characteristics are simulated with feed pressures of 0.1 MPa and 0.4 MPa, respectively. Two planes are chosen for this simulation, which are located in the effective separation region of hydrocyclone (cone angle and apex diameter are 11° and 6 mm respectively). The vertical heights of the two planes are −0.1 m and −0.27 m, respectively, and the former plane named plane I is close to the cylinder section and the latter plane named plane II is more close to the cone bottom of LZVV. The origin of coordinates of the simulation is set at the centre of the circle planes. And the tangential feed orientation is the positive direction of x-coordinate axis. The simulation results are displayed in Figs. 5 and 6.

Figure 5 shows that the tangential velocity isolines in plane I appear like half-circular rings basically. Among all the isolines, those paralleled to the feed orientation occupy more regions than those like circular rings. The length of the main isolines is shortening from the circle centre to the wall gradually. In the meanwhile, the isolines are approximately symmetrical with x-coordinate axis. However, the tangential velocities at the positive direction of z-coordinate axis are lower slightly than those at the negative direction of z-coordinate. From the radial direction vertical to the feed orientation, the highest tangential velocity exists in the region close to the wall of the hydrocyclone. Afterwards the tangential velocities reduce continuously from the wall to the circle center along the radial direction and finally reach zero, which might be explained by the drag force among flows with different tangential velocities. When the feed pressure increases from 0.1 MPa to 0.4 MPa, the distribution characteristics of tangential velocity do not change obviously; however, its magnitude and gradient both increase, which results in the increase of centrifugal force of mineral particles.



(a)



(b)

Fig. 5 Contour (left sides) and vector (right sides) diagrams of tangential velocity in plane I with feed pressure of 0.1 MPa (a) and 0.4 MPa (b)

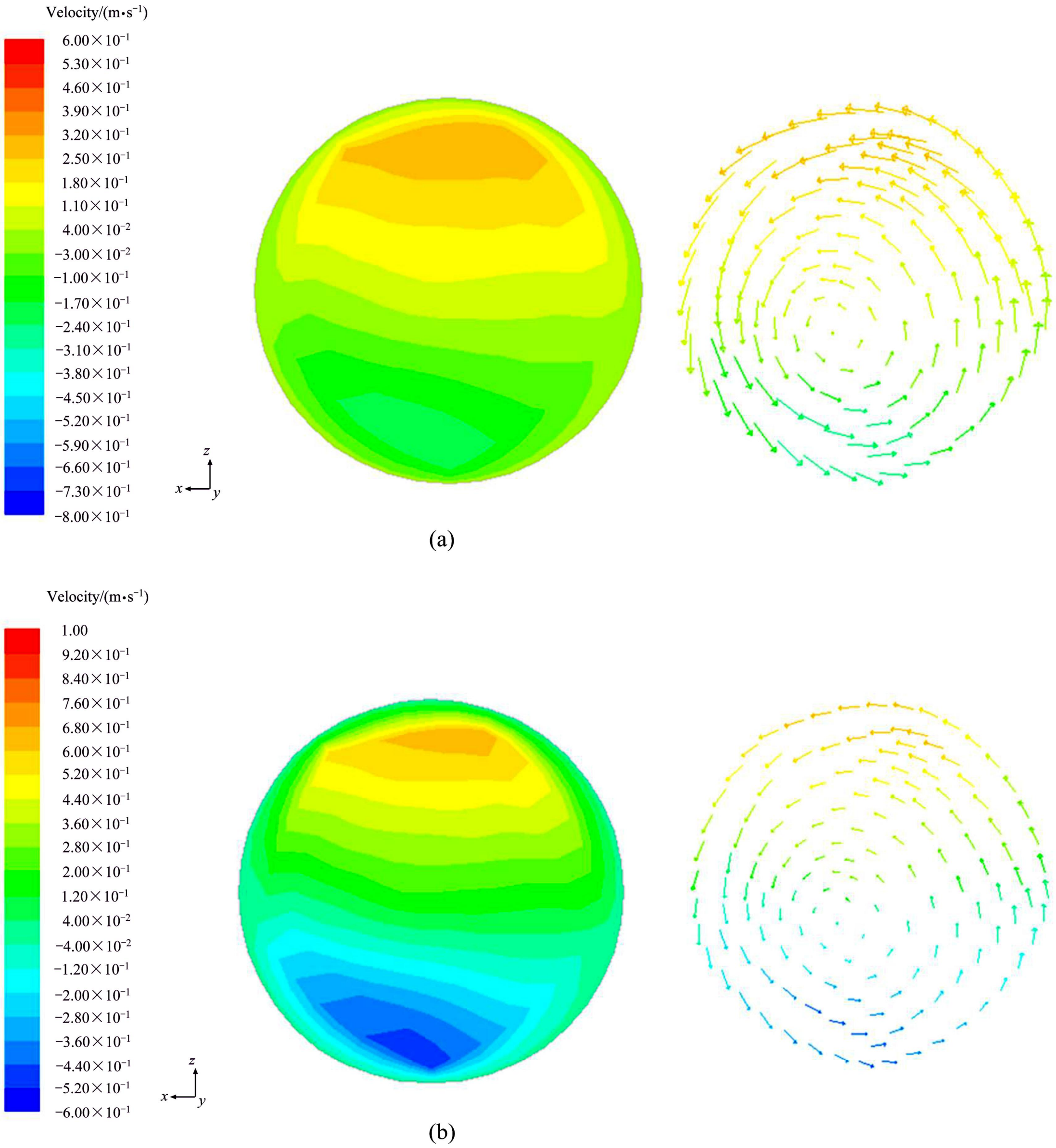


Fig. 6 Contour (left sides) and vector (right sides) diagrams of tangential velocity in plane II with feed pressure of 0.1 MPa (a) and 0.4 MPa (b)

It can also be found from Fig. 6 that the tangential velocity distribution characteristics at plane II is similar to that at plane I. The distinction is that the velocity magnitude of plane II is reduced compared with that of plane I, with a result that the centrifugal force is also reduced. When the feed pressure is increased, the tangential velocity magnitude and gradient both increase accordingly, but the increased extent is not as remarkable as that of plane I. Therefore, the separation effect in the region close to the cone bottom of LZVV is weakened somehow.

The simulation results above show that the flow tangential velocity increases with the increasing of the feed pressure accordingly and leads to the increase of the centrifugal force of solid particles, by which the motion velocity of high density particles to the wall of hydrocyclone could be increased. Therefore, the probability of high density particles to the underflow is increased accordingly and the cyclonic separation effect is improved by the increase of feed pressure. It is also worth mentioning that the simulation results are in accordance with the test results with the same parameters [16]. And the influence decreases along the vertical axis of hydrocyclone from the top to the bottom of LZVV.

4 Conclusions

1) There exist several unsymmetrical envelopes of equal vertical velocities among upward inner flows in hydrocyclone, and the envelope closer to the overflow

pipe has higher velocity. In the downward outer flows, the flow closer to the bottom of the conical section also has higher velocity.

2) Tangential velocity isolines exist in the horizontal planes located in the effective separation region of hydrocyclone, and its magnitude reduces continuously from the wall to the circle center along the radial direction.

3) The structural parameters have remarkable influence on the vertical location of the cone bottom of the envelope of zero vertical velocity. The smaller the cone angle is, the less the influence of apex diameter on the vertical velocity is.

4) The increase of feed pressure has almost no effect on the velocity distribution characteristics of hydrocyclone. However, it can make the magnitude and gradient of tangential velocity increased obviously, resulting in the improvement of particles separation effect.

References

[1] ZHANG Tao, LIANG Hai-jun, XUE Xiang-xin. Recovery of uranium mineral from Liaoning Fengcheng ludwigite ore by gravity concentration [J]. Uranium Mining and Metallurgy, 2009, 28(1): 1−4. (in Chinese)

[2] LI Bin-fei, LI Zhao-min, LI Xiao-hong，FU Lu-chang, ZHANG Zhi-hua. Development of downhole hydrocyclone for liquid-sand separation and its application [J]. Oil Drilling & Production Technology, 2008, 30(1): 121−124. (in Chinese)

[3] WANG Zun-ce, YU Ling-ling, XU Yan, WANG Jia-xin, YUAN Jing-wu. Optimization of the large cone angle parameters of downhole oil/water separation hydrocyclone [J]. Journal of Daqing Petroleum Institute, 2009, 33(2): 78−80. (in Chinese)

[4] HU Yan-hua, LU Chun-xi, SHI Ming-xian. Optimal structure of compact vortex quick separation at FCC riser outlet [J]. Acta Petrolei Sinica, 2009, 25(1): 20−25. (in Chinese)

[5] ZHAO Li-xin, JIANG Ming-hu, SUN De-zhi. Analysis and measurement of the flow field of hydrocyclones [J]. Chemical Engineering & Machinery, 2005, 32(3): 139−142. (in Chinese)

[6] WEI Xin-li, ZHANG Hai-hong, WANG Ding-biao, WU Jin-xing, LIU Hong. Numerical simulation and study of inner flow field in hydrocyclone [J]. Journal of Thermal Science and Technology, 2005(4): 164−168. (in Chinese)

[7] SUTALO I D, PATERSON D A, RUDMAN M. Flow visualization and computational prediction in thickener rake models [J]. Minerals Engineering, 2003, 16: 93−102.

[8] CHU K W, WANG B, YU A B, VINCE A, BARNETT G D, BARNETT P J. CFD-DEM study of the effect of particle density distribution on the multiphase flow and performance of dense medium cyclone [J]. Minerals Engineering, 2009, 22: 893−909.

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

[10] DONG K J, KUANG S B, VINCE A, HUGHES T, YU A B. Numerical simulation of the in-line pressure jig unit in coal preparation [J]. Minerals Engineering, 2010, 23: 301−312.

[11] KOH P T L, SCHWARZ M P. Modelling attachment rates of multi-sized bubbles with particles in a flotaion cell [J]. Minerals Engineering, 2008, 21: 989−993.

[12] BAKKER C W, MEYER C J, DEGLON D A. The development of a cavern model for mechanical flotation cells [J]. Minerals Engineering, 2010, 23: 968−972.

[13] BHASKAR K U, MURTHY Y R, RAJU M R, TIWARI S, SRIVASTAVA J K, RAMAKRISHNAN N. CFD simulation and experimental validation studies on hydrocyclone [J]. Minerals Engineering, 2007, 20: 60−72.

[14] WEERASEKARA N S, GARCIA FRUTOS F J, CARA J, LOCKWOOD F C. Mathematical modeling of demineralization of high sulphur coal by bioleaching [J]. Minerals Engineering, 2008, 21: 234–240.

[15] GAO Shu-ling, LI Xiao-an, WEI De-zhou, FANG Ping, JIA Chun-yun, LIU Wen-gang, HAN Cong. Beneficiation of low-grade diasporic bauxite with hydrocyclone. [J]. Transactions of Nonferrous Metals Society of China, 2008, 18(2): 444−448.

[16] GAO Shu-ling. Study on separation behavior of diasporic low-grade bauxite in cyclonic field [D]. Shenyang: Northeastern University, 2009: 47−52. (in Chinese)

基于 CFD 的旋流器内流速特征的数值模拟

高淑玲，魏德洲，刘文刚，马龙秋，卢　涛，张瑞洋

东北大学 资源与土木工程学院，沈阳 110004

摘　要：为了查清旋流器内流速分布特征及其影响机理，在不同的结构参数和操作参数条件下，对旋流器内流速进行基于 CFD 方法的数值模拟。结果表明，在旋流器的内旋流和外旋流中均存在非对称的等轴向速度面，而且旋流器锥角和底流口直径对零轴向速度面锥底点的轴向空间位置具有显著的影响。另外，在旋流器有效分离区域内的水平面上存在切向速度的等值线。入口压强对轴向速度分布特征和切向速度分布特征的影响不显著，但可使切向速度及梯度明显增大，致使高密度颗粒向边壁的运动速度加快，从而使旋流分选的作用加强。

关键词：数值模拟；旋流器；流速特征；结构参数；操作参数；旋流分选作用

(Edited by YANG Hua)