CHEMICAL ENGINEERING TRANSACTIONS
VOL. 66, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Songying Zhao, Yougang Sun, Ye Zhou

ISBN 978-88-95608-63-1; **ISSN** 2283-9216
DOI: 10.3303/CET1866072

Analysis of Random Features of Turbulent Process in Hydrocyclone Based on Computational Fluid Mechanics

Yayun Fan*, Jingjing Feng, Xiaowei Zhang

School of Intelligent Science and Information Engineering, Xi'an Peihua University, Xi'an 710125, China
ziyun50051@163.com

This paper simulates and analyzes the flow field characteristics and the random features of particle trajectories inside a hydrocyclone based on computational fluid dynamics, constructs a turbulent model for the random separation of particles, and investigates the velocity of hydrocyclone in different directions and the discharge methods of particles. The conclusion of the study shows that the flow field velocity on both sides of the hydrocyclone axis is not the same, which proves that the internal flow field of the hydrocyclone is asymmetric. In terms of radial velocity, the farther away from the axial center of the hydrocyclone is, the smaller the radial velocity is; and the closer it is to the axial center, the greater the velocity oscillation is. In terms of the axial velocity, there is a gradual-change zone in the position far away from the axis, where the turbulence and backflow inside the flow field interact with each other to form a multi-layered vortex, and the vortex appears in an unfixed and asymmetrical position. The eddies of the turbulence have a much greater influence on the radial velocity than on the axial velocity, and the existence of the gradual-change zone will cause an uneven concentration distribution within the hydrocyclone. The particle separation effect of the hydrocyclone is related to the position from which the particles injected into the container, the farther away the particle injection point is, the longer the particles stay in the external swirl, and the easier the particles are discharged from the bottom of the hydrocyclone. The trajectories of the particles have large discreteness.

1. Introduction

Hydrocyclone is mainly used for the separation of liquids and solids, separation of oil and water, particle sorting, etc. It has the advantages of simple structure, simple manufacturing process and large amount of product processing. Since invented in 1940, it has been widely used in petrochemical industry, medicine, mining, construction and other fields (Hsieh and Rajamani, 2010; Coelhoa and Medronho, 2001).

The internal flow field of the hydrocyclone is extremely complicated. After years of studies by the researchers, it is currently believed that the internal flow field of the hydrocyclone includes internal/external turbulence, circulating turbulence, line of zero vertical velocity (LZVV), air column, etc. (Zhang et al., 2011; Bergström and Vomhoff, 2007; Liu et al., 2016; Li and Hu, 2013). Correspondingly, the researchers proposed turbulence model, equilibrium orbit model, empirical model, and obstruction model for quantitative characterization (Delgadillo and Rajamani, 2005; Chen, Zydek and Parma, 2000). Since the parameters such as fluid pressure and solution concentration inside the hydrocyclone are constantly changing, the above theoretical models all have different degrees of defects (Wang et al., 2012; Song et al., 2013; Wang et al, 2017).

With the continuous development of computer technology, computer simulation based on computational fluid dynamics can better solve the defects of the above theoretical analysis (Xu et al., 2013; Cullivan et al, 2004). Related literatures have studied the internal separation and particle sorting of hydrocyclone through numerical analysis methods, and focus on the analysis of the hydrocyclone's separation performance and optimization of the structure (Wang et al., 2007; Jin and Yuan, 2011; Wang et al, 2006). For the random features of particle motion and the turbulent process in hydrocyclone, there are very few related studies (Matvienko, 2004; Matvienko et al., 2014).

Based on computational fluid dynamics, the characteristics of the flow field inside the hydrocyclone and the random features of particle trajectories were simulated and analyzed in this paper. The turbulence model for

Please cite this article as: Fan Y., Feng J., Zhang X., 2018, Analysis of random features of turbulent process in hydrocyclone based on computational fluid mechanics, Chemical Engineering Transactions, 66, 427-432 DOI:10.3303/CET1866072

the random separation of particles was constructed, and the velocity of the hydrocyclone in different directions and the particle discharge method were investigated.

2. Turbulence model and numerical calculation method of hydrocyclone based on computational fluid dynamics

In the hydrocyclone, the equation of continuous motion of incompressible media is:

$$\frac{\partial U_t}{\partial x_t}=0 \tag{1}$$

$$\rho\left(\frac{\partial U_t}{\partial t}+u_j\frac{\partial U_t}{\partial x_j}\right)=-\frac{\partial p}{\partial x_t}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_t}{\partial x_j}+\frac{\partial U_j}{\partial x_t}\right)-\rho\overline{u_t'u_j'}\right]+\rho g_t \tag{2}$$

Using Reynolds Stress Equation to close formula 2:

$$\rho\frac{D\overline{u_t'u_j'}}{Dt}=\frac{\partial}{\partial x_l}\left(\frac{\mu_t}{\sigma_k}\frac{\partial\overline{u_t'u_j'}}{\partial x_l}+\mu\frac{\partial\overline{u_t'u_j'}}{\partial x_l}\right)+P_{tj}-\frac{2}{3}\delta_{tj}\rho\varepsilon+\Phi_{tj} \tag{3}$$

The turbulent kinetic energy is:

$$\rho\frac{Dk}{Dt}=\frac{\partial}{\partial x_l}\left[\left(\frac{\mu_t}{\sigma_k}+\mu\right)\frac{\partial k}{\partial x_l}\right]-\rho\overline{u_t u_l}\frac{\partial U_t}{\partial x_l}-\rho\varepsilon \tag{4}$$

The consumption of turbulent kinetic energy:

$$\rho\frac{D\varepsilon}{Dt}=\frac{\partial}{\partial x_l}\left[\left(\frac{\mu_t}{\sigma_s}+\mu\right)\frac{\partial\varepsilon}{\partial x_l}\right]-C_{s1}\frac{\varepsilon}{k}\frac{\mu_t}{2}\left(\frac{\partial u_t}{\partial x_j}+\frac{\partial u_j}{\partial x_t}\right)^2-C_{s2}\rho\frac{\varepsilon^2}{k} \tag{5}$$

Formula 1-5 are the Reynolds stress model. Using formula 1-5 to check the turbulence model in the hydrocyclone.

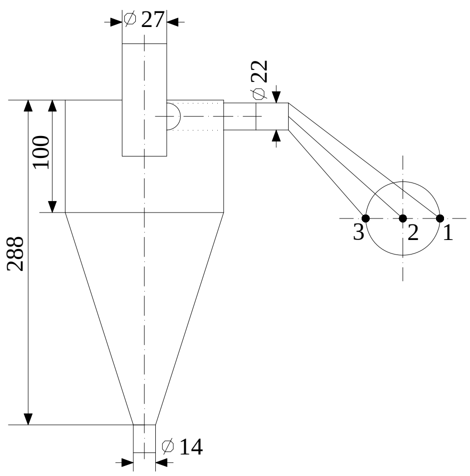

Figure 1: Size of the hydrocyclone and the position of particle injection

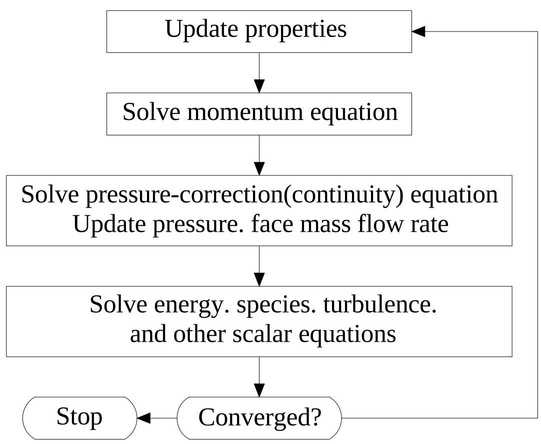

Figure 2: Separation numerical calculation process of turbulence model

Figure 1 shows the size of the hydrocyclone and the position of particle injection.
To summarize above introductions, we can get the separation numerical calculation process of the turbulence model of the hydrocyclone, as shown in Figure 2.

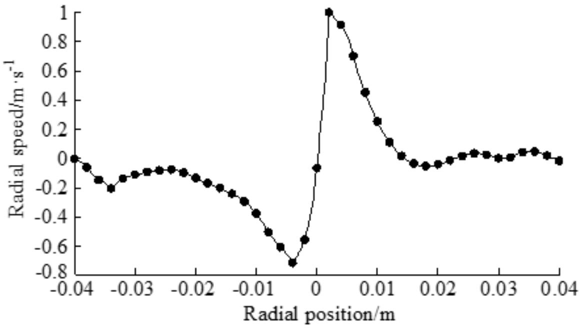

Figure 3: Radial velocity distribution of the hydrocyclone

3. Hydrocyclone flow field simulation results and analysis

According to the CFD simulation mechanism in the previous section, the flow field related parameters of the hydrocyclone were simulated. Figure 3 shows the velocity change inside the hydrocyclone in the radial direction. As can be seen from the figure, the velocity at the wall of both ends of the hydrocyclone is basically zero, and the closer the distance to the axis, the faster the velocity begins to increase. When the distance from the axis is about 5 mm, the velocity is the highest, about 0.9m/s. At the column segment, the radial velocity oscillates violently in the external vortex, while only slightly changes in the internal vortex flow, indicating that the random fluctuation of the flow field of the hydrocyclone occurs mainly in the external vortex. It can also be seen from Figure 3 that the velocities on both sides of the hydrocyclone axis are not the same, indicating that the internal flow field of the hydrocyclone is asymmetric.

Figure 4 shows the radial velocity at the distance of 100mm and 150mm from the top cover of the hydrocyclone. As can be seen from the figure, at 100mm and 150mm, the radial velocity changes are the same for both positions, the farther from the axis, the smaller the radial velocity, the closer it is to the axis, the larger the velocity oscillation is. But for the two positions, the directions of the maximum radial velocity are opposite, which is due to the opposite directions of the deflection of the inner air core of the hydrocyclone.

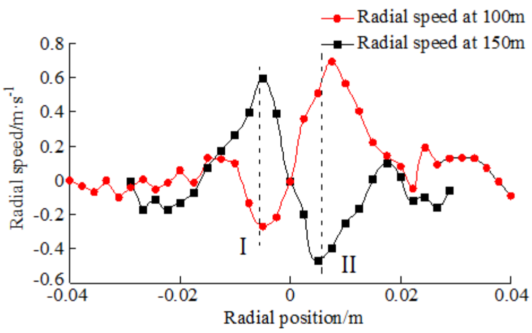

Figure 4: Radial velocity at the distance of 100 mm and 150 mm from the top cover of the hydrocyclone

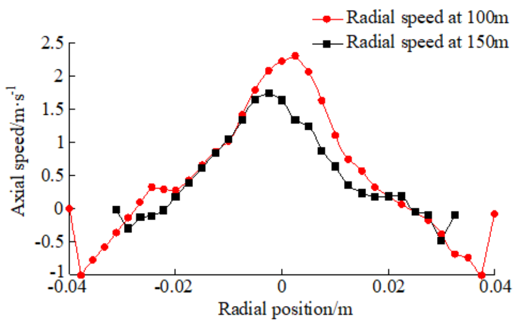

Figure 5: Axial velocity at the distance of 100 mm and 150 mm from the top cover of the hydrocyclone

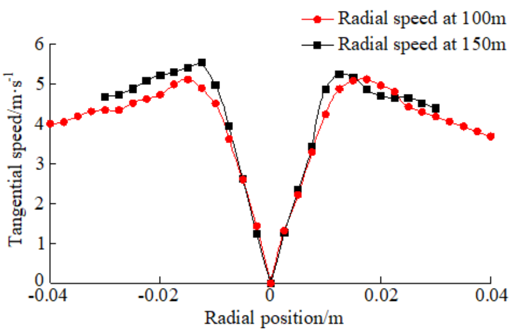

Figure 6: Tangential velocity at the distance of 100 mm and 150 mm from the top cover of the hydrocyclone

Figure 5 shows the axial velocity at the distance of 100 mm and 150 mm from the top cover of the hydrocyclone. As can be seen from the figure, both the trend of change and the maximum radial velocity are kept in sync with each other, and the external swirling flow and the internal swirling flow are in the opposite directions. There is a gradual-change zone in the position far away from the axis, which is caused by the multi-layer vortex formed by the interaction of turbulence and backflow inside the flow field, and the position of the vortex is not fixed and asymmetric. Comparing Figure 4 and Figure 5, the effect of turbulent eddies on radial velocity is much greater than that of phase velocity. The existence of the gradual-change zone will cause an uneven concentration distribution within the hydrocyclone, so that random irregular motion of graded particles appears, and thus affects the separation effect of the hydrocyclone.

Figure 6 shows the tangential velocity at the distance of 100 mm and 150 mm from the top cover of the hydrocyclone. As can be seen from Figure 6, the flow line of the short-circuit flow appears outside the column section of the hydrocyclone, and the flow lines are asymmetrically distributed; the secondary eddies appear at the end of the overflow pipe, when the inlet speed of the hydrocyclone increases, the secondary eddies increase accordingly.

4. Random feature analysis of particle motion trajectory in the hydrocyclone

Here we further analyze the random features of the internal particle motion trajectory in the hydrocyclone. In the experiment, vegetable seeds were used to replace the particles in the project and water was used as the liquid carrier. The particle diameter is 0.6-1.1mm; the inlet flow rate is set to 2-5m^3/h; the hydrocyclone cone angle is set to 10-50°. The particle injection point is shown in Figure 1.

Figure 7-9 shows that when the particles are injected twice from the same position (Point 1, 2 or 3), the trajectories of the particles are completely different, which proves that the internal particle motion of the hydrocyclone presents irregular random movement features.

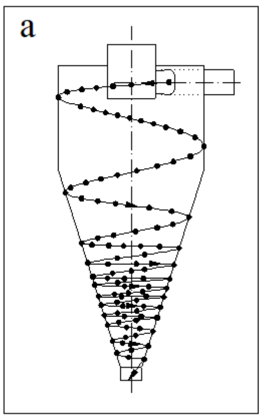

Figure 7: Random motion trajectory of particles when injected into the hydrocyclone from Point 1

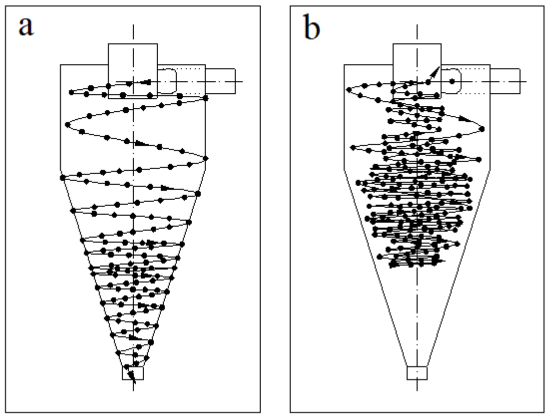

Figure 8: Random motion trajectory of particles when injected into the hydrocyclone from Point 2

For each position, first we can see from Figure 7 that, the particles are injected from Point 1 and flow out from the bottom under the condition of (a), and the pattern of their movement is quite obvious; under the condition of (b), the particles overflowed from the top, and their movement shows obvious randomness. Under both conditions of (a)(b), the particles can reach about 1/3 of the bottom of the hydrocyclone.

As can be seen from Figure 8, the number of the particles that are injected from Point 2 and overflowed from the overfall on the top is more than that of the particles of Point 1, and a considerable part of the particles only reach the position of 1/2 of the bottom. At the same time, the screw value of the particles injected from Point 2 is smaller, at the positions of 1/3 and 1/2 from the bottom, there is floating phenomenon for partial particles, which is unfavorable for the classification and separation of the particles.

As can be seen from Figure 9, only a small part of the particles injected from Point 3 are discharged from the bottom of the hydrocyclone, while the particles discharged from the overfall on the top can only reach up to the position at which the cylinder surface and the conical surface of the hydrocyclone intersect (at the position of 2/3 from the bottom), so that particle short-circuit flow occurs inside the hydrocyclone, which is even more detrimental to particle grading.

Based on the experimental results in Figures 7-9, it can be seen that the particle separation effect of the hydrocyclone is related to the position from which the particles are injected into the container, the farther away the particle injection point is, the longer the particles stay in the external swirl, and the easier the particles are discharged from the bottom of the hydrocyclone. Under the condition of same particle properties, external pressure, and particle injection position, the particle trajectories still exhibit large discreteness. This case proves the random features of the flow field inside the hydrocyclone.

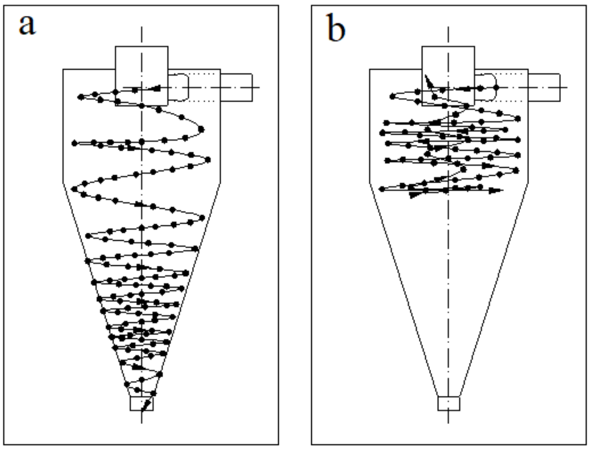

Figure 9: Random motion trajectory of particles when injected into the hydrocyclone from Point 3

Figure 10 and 11 show the motion trajectories of particles which are discharged from bottom and top of the hydrocyclone and injected from Point 1, and with the particle diameter of 0.7 mm and 0.9 mm. It can be seen from the figure that when the particle diameter is 0.7mm, the middle and lower part of the hydrocyclone appears obvious particle floating phenomenon, overall, 0.7mm particle have a larger screw value at the position of 2/3 from the bottom, and relatively smaller screw value at the position of 1/3 from the bottom; when the particle size increases to 0.9mm, the screw values of the particles in each position inside the hydrocyclone are all greater than 0.7mm, it is because larger particles are less affected by turbulence and are subject to greater stress in the axial direction.

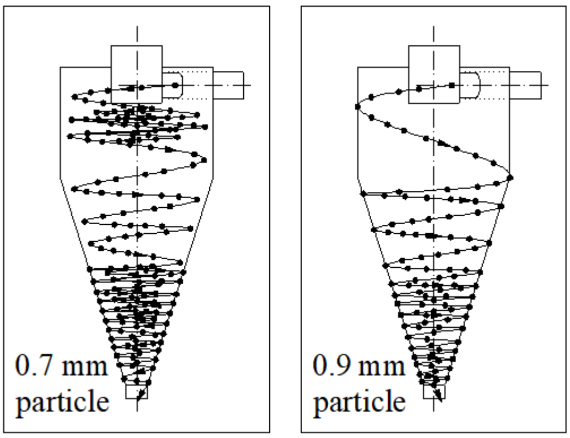

Figure 10: The motion trajectory statistics of particles discharged from the bottom with particle diameters of 0.7mm and 0.9mm

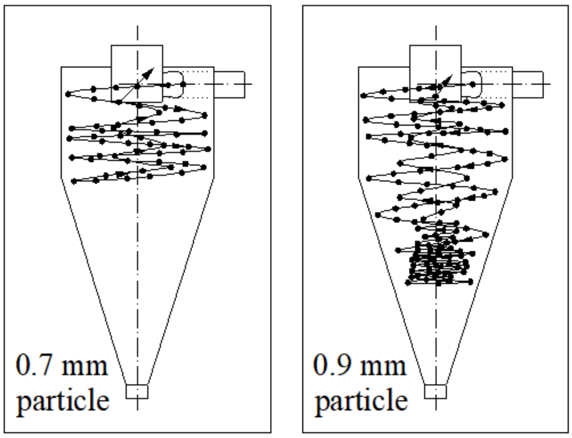

Figure 11: Statistics of motion trajectories of particles discharged from the top with particle diameters of 0.7mm and 0.9mm

5. Conclusion

Based on computational fluid dynamics, the characteristics of the flow field inside the hydrocyclone and the random features of particle trajectories were simulated and analyzed in this paper. The turbulence model for the random separation of particles was constructed, the velocity of the hydrocyclone in different directions and the particle discharge methods were investigated. The conclusions of the research are as follows:

(1) The flow field velocity on both sides of the hydrocyclone axis is not the same, which proves that the flow field inside the hydrocyclone is asymmetric. In terms of radial velocity, the farther away from the axial center of the hydrocyclone is, the smaller the radial velocity is; and the closer it is to the axial center, the greater the velocity oscillation is. In terms of the axial velocity, there is a gradual-change zone in the position far away from the axis, where the turbulence and backflow inside the flow field interact with each other to form a multi-layered vortex, and the vortex appears in an unfixed and asymmetrical position. The eddies of the turbulence have a much greater influence on the radial velocity than on the axial velocity, and the existence of the gradual-change zone will cause an uneven concentration distribution within the hydrocyclone.
(2) The particle separation effect of the hydrocyclone is related to the position from which the particles are injected into the container, the farther away the particle injection point is, the longer the particles stay in the external swirl, and the easier the particles are discharged from the bottom of the hydrocyclone. The particle trajectories exhibit large discreteness. The larger the size of the particles is, the larger their motion screw value is, this is because larger particles are less affected by turbulence and are more subjected to the stress in the axial direction.

Reference

Bergström J., Vomhoff H., 2007, Experimental hydrocyclone flow field studies, Separation & Purification Technology, 53(1), 8-20, DOI: 10.1016/j.seppur.2006.09.019

Chen W., Zydek N., Parma F., 2000, Evaluation of hydrocyclone models for practical applications, Chemical Engineering Journal, 80(1-3), 295-303, DOI: 10.1016/s1383-5866(00)00105-2

Coelhoa M.A.Z., Medronho R.A., 2001, A model for performance prediction of hydrocyclones, Chemical Engineering Journal, 84(1), 7-14, DOI: 10.1016/s1385-8947(00)00265-5

Cullivan J.C., Williams R.A., Dyakowski T., Cross C.R., 2004, New understanding of a hydrocyclone flow field and separation mechanism from computational fluid dynamics, Minerals Engineering, 17(5), 651-660, DOI: 10.1016/j.mineng.2004.04.009

Delgadillo J.A., Rajamani R.K., 2005, A comparative study of three turbulence-closure models for the hydrocyclone problem, International Journal of Mineral Processing, 77(4), 217-230, DOI: 10.1016/j.minpro.2005.06.007

Li H., Hu R., 2013, Research on the inner water flow field in a hydrocyclone by the method of 3d numerical simulation, Journal of Applied Sciences, 13(22), 5235-5239, DOI: 10.3923/jas.2013.5235.5239

Liu B., Xu J., Wang Y., 2016, The numerical simulation of the inside flow field of oil-water hydrocyclone with different structures, The Workshop on Advanced Research & Technology in Industry Applications, DOI: 10.2991/wartia-16.2016.205

Matvienko O.V., Andropova A.O., Agafontseva M.V., 2014, Influence of the regime of flow of particles from a hydrocyclone on its separation characteristics, Journal of Engineering Physics & Thermophysics, 87(1), 24-37, DOI: 10.1007/s10891-014-0981-9

Matvienko O.V., 2004, Analysis of turbulence models and investigation of the structure of the flow in a hydrocyclone, Journal of Engineering Physics & Thermophysics, 77(2), 316-323, DOI: 10.1023/b:joep.0000028510.57907.87

Song R.F., Yang Y.T., Zhao L., Fang F., 2013, Numerical simulation on two inlet structure of hydrocyclone, Advanced Materials Research, 803, 399-403, DOI: 10.4028/www.scientific.net/amr.803.399

Su J., 2011, Separation efficiency optimization of liquid-solid hydrocyclone and numerical simulation, Journal of Mechanical Engineering, 47(20), 183, DOI: 10.3901/jme.2011.20.183

Wang B., And K.W.C., Yu A.B., 2007, Numerical study of particle−fluid flow in a hydrocyclone, Industrial & Engineering Chemistry Research, 46(13), 4695-4705, DOI: 10.1021/ie061625u

Wang L.Y., Zheng Z.C., Guo J., Zhang J., Tang C., 2006, Investigation on separation efficiency of liquid/solid hydrocyclone, Journal of Hydrodynamics Ser B, 18(3), 400-404, DOI: 10.1016/s1001-6058(06)60085-1

Wang Y., Zhao L.X., Wang Y.W., Xu B.R., Jiang M.H., University N.P., 2017, Contrastive analysis on numerical simulation of oil-water hydrocyclone with various inlet forms, Fluid Machinery, 7.

Wang Z.C., Zhang J.L., Xu Y., Ji Y.B., 2012, Numerical simulation of oil-water flow in dynamic hydrocyclone with different operating parameters, Chemical Engineering & Machinery, 2.

Xu H., Chen X.H., Yao Y., 2013, Hydrocyclone velocity flow simulation and experimental study based on fluid mechanics, Advanced Materials Research, 625, 113-116, DOI: 10.4028/www.scientific.net/amr.625.113

Zhang F.L., Deng S.S., Hua W.X., 2011, Numerical simulation for flow field in hydrocyclone, Advanced Materials Research, 335-336, 683-687, DOI: 10.4028/www.scientific.net/amr.335-336.683