Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 11 (12): 2179-2185, 2011
ISSN 1812-5654 / DOI: 10.3923/jas.2011.2179.2185

Development of a Cone Vortex Stabilizer to Improve Cyclone Separator Performance

[1]Masoud, Dorfeshan and [2]Shahram Hashemi Marghzar
[1]Department of Mechanical Engineering, Behbahan Higher Education Complex,
Behbahan, Khoozestan, Iran
[2]Department of Mechanical Engineering, Shahrood University of Technology, Semnan, Shahrood, Iran

Abstract: This study presents the results of numerical and experimental simulation of flow pattern in a cyclone separator in sulfur granulation process. For the first time, a cone vortex stabilizer has been used to improve cyclone efficiency. The flow features are examined in terms of flow field, pressure drop, particle trajectories and separation efficiency. In this study, grade efficiencies have been computed and compared with the experimental values for cyclones of different cone stabilizer dimensions. The results show that the separation efficiency rising with the use of the cone stabilizer and the main reason of it is the reduction of particle escaping from cone body of cyclone to upward flow.

Key words: Vortex stabilizer, cyclone separator, grade efficiency, particle phase modeling, turbulence modeling, pressure drop

INTRODUCTION

Cyclone separators are still the cheapest and the most reliable equipment for dust separation from gases. Due to low, manufacturing and maintenance costs, simple operation and flexibility, cyclone separator has been preferably utilized in various industrial operations including powder processing. However, low collection efficiency of large scale cyclones for particles smaller than 5 mm has been indicated as a disadvantage, specifically when stringent regulation on air discharge of particulate essentially calls for invisible stack emission. Since its inception over a century ago, many researchers have contributed to the large volume of work on improving the efficiency of cyclone by introducing new design and operation variables (Jiao and Zheng, 2007).

However, in most cases, the improvement in efficiency is marginal, but there is a potential for improving cyclone separators as discussed in the following. Recently, a number of variation and modifications of geometrical variables to the basic design of gas cyclone and hydrocyclone have been examined by various investigations to find out optimal models for different industrial applications (Avci and Karagoz, 2003; Yalcin *et al.*, 2003; Grommers and Krikken, 2004; Wang and Yu, 2006; Bhaskar *et al.*, 2007; Neesse *et al.*, 2007). Also many researches have been focused on operational variables like feed inlet pressure, particle concentration, gas velocity, temperature, turbulence intensity, etc. (Fassani and Goldstein, 2000; Mukherjee *et al.*, 2003; Xiaodong *et al.*, 2003; Cilliers *et al.*, 2004; Neesse *et al.*, 2004; Yang *et al.*, 2004; Bernnan *et al.*, 2007; Magwai and Bosman, 2007).

In the petroleum industry, where a sulfur granulation process is employed, cyclones operate under medium solid loading. Their application is recommended for being capable to ensure steady state operation, recycling the sulfur back to the process and preventing its emission to the atmosphere.

In this study, the new cone vortex stabilizer was developed for the first time and numerical and experimental studies on addressing the effect of vortex stabilizer on cyclone performances are presented. The cyclone geometry used for simulation and for experimental studies is presented in Fig. 1.

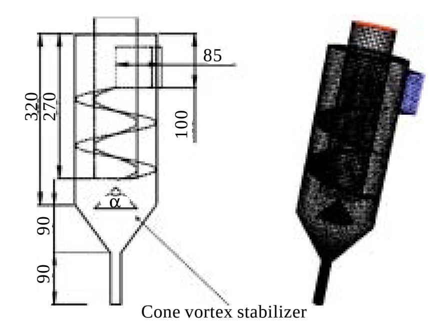

Fig. 1: Detailed dimensional drawing of dense medium cyclone used for simulation and experiment

Corresponding Author: Masoud Dorfeshan, Department of Mechanical Engineering, Behbahan Higher Education Complex, Behbahan, Khoozestan, Iran Tel: +989163523193 Fax: +986712231376

THEORETICAL CONSIDERATION

Turbulence modeling: The flow field in gas cyclones is a strong turbulent swirling flow. In the Computational Fluid Dynamics (CFD) modeling of gas cyclone, the Reynolds averaged Navier-Stokes equations a suitable turbulence model should supplement (RANS). The choice of the turbulence model is very important for adequate solving of the highly swirling flows within a gas cyclone. Researchers use many turbulence models in recent years such as:

k-εmodel, algebraic stress model (ASM) and Reynolds stress model (RSM). The k-ε model adopts the assumption of isotropic turbulence, so it is not suitable for the flow in a cyclone, which has anisotropic turbulence. ASM cannot predict the circulation zone and Rankine vortex in strongly swirling flow (Sun and Li, 2002). RSM forgoes the assumption of isotropic turbulence and solves a transport equation for each component of the Reynolds stress. It is regarded as the most applicable turbulent model for cyclone flow even though it has the disadvantage of being computationally more expensive (Lee *et al*., 2006). When using the Reynolds stress turbulence model, beside the momentum and continuity equations, the transport equations of Reynolds stresses can be written as:

$$\frac{\partial}{\partial t}\left(\rho\overline{u_i u_j}\right)+\frac{\partial}{\partial x_k}\left(\rho U_k\frac{\overline{u_i u_j}}{\partial x_k}\right)=P_{ij}+\varphi_{ij}+D_{ij}+\varepsilon_{ij} \tag{1}$$

where, the four terms on the right hand side stand for stress diffusion, stress production, pressure strain and dissipation terms, respectively. The stress diffusion and the production are exact; however, the remaining terms need to be modeled in order to close the equations.

Particulate phase modeling: In the gas cyclone system operating since the particulate is very dilute, its effects on the flow field was not considered (Chuah *et al*., 2006). The continuous gas flow was solved first. The discrete particulate phase is predicted based on the fixed continuous phase flow field. The trajectory of the discrete phase particle is obtained by integrating the force balance on the particle, which can be written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle and can be written as:

$$\frac{dU_{P_i}}{dt}=F_D(U_i-U_{P_i})+\frac{(\rho_p-\rho)g_i}{\rho_p} \tag{2}$$

where, U_{pi} is the particle velocity (I = x,y,z), U_i is the gas velocity, ρ_p and ρ are the density of the particle and the gas, respectively. $F_D(U_i\text{-}U_{pi})$ is the drag force per unit particle mass and F_D is given by:

$$F_D=\frac{18\mu}{\rho_p d_p^2}\frac{C_D\,Re}{24} \tag{3}$$

where, d_p is the particle diameter, μ is the dynamic viscosity of the gas, Re is the relative Reynolds number, which is defined as:

$$Re\equiv\frac{\rho\, d_p\left|U_p-U\right|}{\mu} \tag{4}$$

The drag coefficient C_D can be calculated by:

$$C_D=\begin{cases}\frac{24}{Re C_c} & Re<0.1\\ \frac{24}{Re}(1+0.15Re^{0.687}) & 0.1<Re<500\\ 0.44 & 500<Re<2\times10^5\end{cases} \tag{5}$$

Drag law was implemented by a user-defined function based on the above C_D Equations. The magnitude of the Cunningham correction factor C_C, is given by:

$$C_c=1+\frac{2\lambda}{d_p}(1.257+0.4e^{-(1.1d_p/2\lambda)}) \tag{6}$$

In which λ is the mean free path of the gas molecules. The trajectory equation is described as:

$$\frac{dx_i}{dt}=u_{Pi} \tag{7}$$

Because the particle diameter is in the range of 1-10 μm, the effect of the instantaneous turbulent velocity fluctuations on the particle trajectories can not be ignored. Therefore, the stochastic tracking model has been used in this simulation.

Boundary condition: The grids consist of about 225000 control volumes for the cyclone. Grid refinement tests are conducted in order to make sure that the solution is not grid dependent. A "velocity inlet" boundary condition was used at the cyclone inlet and the inlet velocity was 11 m sec^{-1} in each simulation. The boundary condition at the gas exit used was the out-flow condition (Qian *et al*., 2007). No slip boundary condition was used in wall boundary and near-wall treatment was standard wall function. Referring to the convergence criteria; two aspects should be paid attention to. On the one hand, the scaled residuals are below 10^{-1}; on the other hand, some representative quantities such as velocity and pressure should be monitored and when these values do not change, the solving process is converged. The iteration number of every case is about 13000-15000 times. The CFD simulation was performed with a Pentium IV Core2 Due 2.5 GHz with 1 GB RAM-memory and 250 GB hard disc memory.

EXPERIMENTAL SETUP

The objective of this experiment is to validate the numerical results and the visualization of the sulfur particle trajectories. In the laboratory, tests were carried out at controlled conditions following design of experiments to find out the effect of cone vortex stabilizer on performance of cyclone separator. Seven kinds of cyclones were studied by varying cone stabilizer from 90 to 150° of cone angle. Laboratory experiments were carried out with sulfur dust sample received from Razi sulfur granulating complex (mean particle size: 5 microns, particle density: 2065 kg m^{-3}).

Inlet size distribution was periodically checked and remained constant. Particle flow rate and overall separation efficiency were obtained at the end of each test run by weighting collected particles inside the dustbin. Samples of particles were collected to obtain grade efficiencies. To minimize the experimental errors, the measurements were carried out 3-5 times and the arithmetically averaged values were taken as the results. To check the reliability of the mass balance, samples were simultaneously taken from all the feed, underflow and overflow and then the solid weight concentrations and the particle size distributions of the samples were measured.

RESULTS

Gas flow field: Cyclone performance is evaluated in terms of pressure drop and collection efficiency. To assess factors that contribute to performance, the tangential, radial. And axial velocity components of the velocity field must be understood.

Pressure drop: The pressure drop over a cyclone consists of a local loss and a frictional loss (or a loss along the distance). The local loss includes an expansion loss at the cyclone inlet, ΔP1 and a contraction loss at the entrance of the outlet tube, ΔP2. The frictional loss includes a swirling loss due to the friction between the gas flow and the cyclone wall, ΔP3 and a dissipation loss of the gas dynamic energy in the outlet, ΔP4 (Chen and Shi, 2007). Therefore, the pressure drop can be expressed as:

$$\Delta P = \Delta P1+\Delta P2+\Delta P3+\Delta P4 \qquad (8)$$

The pressure drop across cyclone is commonly expressed as a number of gas inlet velocity heads ΔH named the pressure drop coefficient, which is the division of the pressure drop by inlet kinetic pressure $\rho_g v_i^2/2$.

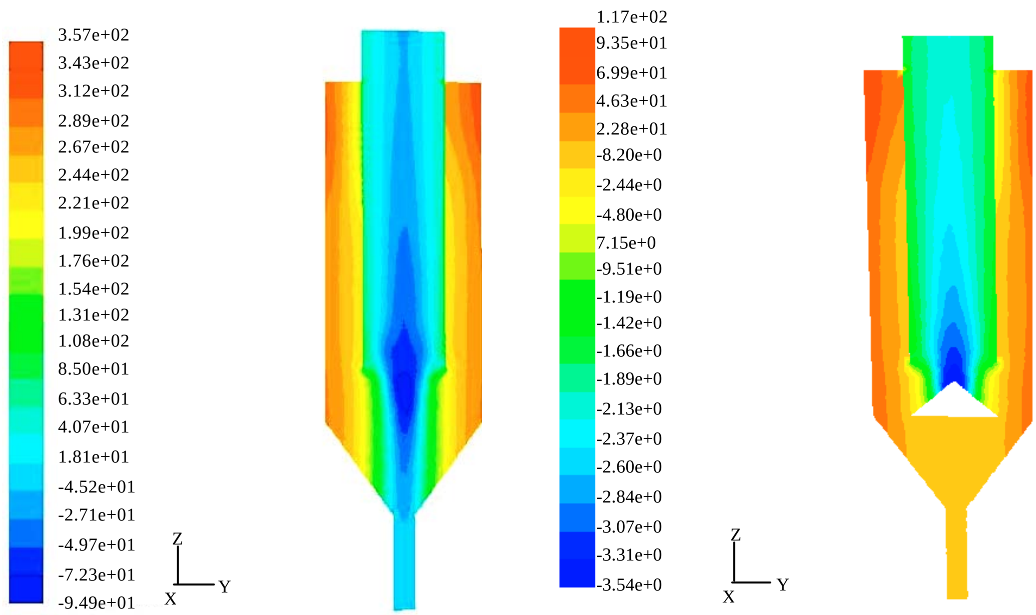

Fig. 2: Evolution of pressure drop for inlet velocity of 11 m sec^{-1}. comparison between conventional and new design cyclone

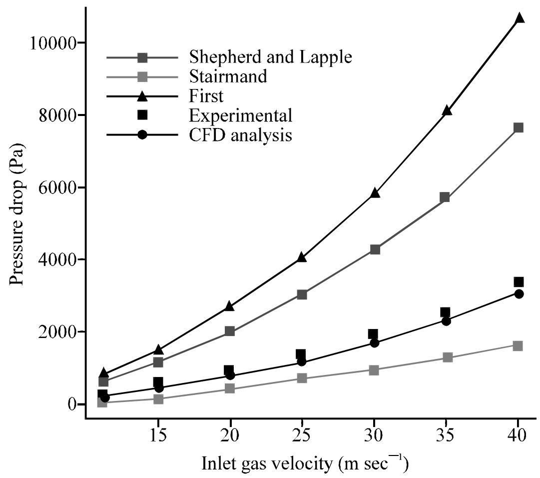

Fig. 3: Compares the results of CFD and experimental analysis for this study with results of other theoretical methods

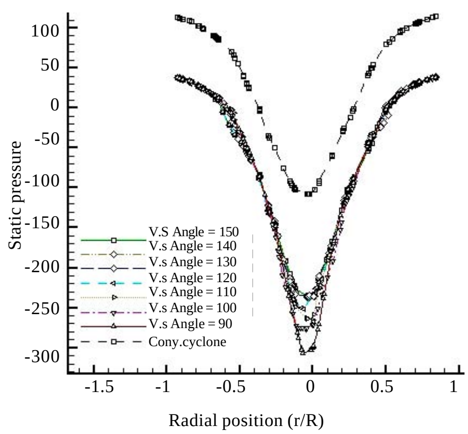

Fig. 4: Static pressure profile along the entrance of vortex finder. Comparison between conventional and new design cyclone with various cone stabilizer angles

Figure 2 shows that the static pressure decreases radially from wall to centre and a negative pressure zone appears in a centre. The pressure gradient is the largest along radial direction, as there is a highly intensified forced vortex.

Figure 3 shows the relationship between the pressure drop and the inlet gas velocity and compares the CFD results with three theoretical methods. Apparently, the pressure drop curve based on Stairmand's model match the experimental curves much closer than other theories do.

Figure 4 compares the pressure profile along the entrance of vortex finder between conventional and new design cyclone with various cone stabilizer angles.

Tangential velocity: The tangential velocity is prerequisite for particle separation from the fluid and mainly determines the flow pattern in the cyclone and its value reflects the loss of swirling kinetic energy. Figure 5a and b show that the tangential velocity in a cyclone exhibits a combined vortex structure. In this state the tangential velocity increases with increasing radius in the neighborhood of the axis, which is called quasi forced vortex. Also the tangential velocity reaches a maximum approximately at the vortex finder radius and decreases thereafter with increasing radius, which is called quasi free vortex.

The maximum tangential velocity is located at 0.75-0.85 radius of the vortex finder. As a whole, the greater angle of vortex stabilizer has a smaller tangential velocity in near wall zone of vortex finder.

Axial velocity: The increment of the turbulent will make the particle enter the zone where the axial velocity of the gas phase is upward which gives a good explanation of why the separation efficiency of the relatively smaller particles decreases with increase in the turbulence intensity. The cone vortex stabilizer angle of 90° causes a decrease of the maximum tangential velocity of generally about 2.75 m sec^{-1}. while the cone vortex stabilizer angle of 150° causes a decrease of about 5.1 m sec^{-1}. As a whole, the greater angle vortex stabilizer has a maximum and minimum axial velocity in near wall zone and center of vortex finder, respectively. Figure 6 compares the axial velocity profile along the entrance of vortex finder between conventional and new design cyclone with various cone stabilizer angles.

Separation efficiency: Separation efficiency in a cyclone is the fraction of the inlet solid flow rate separated in the cyclone. As a cyclone usually collects a wide solid inlet distribution, it is common to express the cyclone efficiency as a function of the particle size, leading to the fractional efficiency curve.

To obtain the optimum cone stabilizer, grade efficiencies have been computed and compared with the experimental values for cyclones of different cone stabilizer dimensions. The main reason of the separation efficiency rising with the use of cone stabilizer is the reduction of particle escaping from cone body of cyclone.

The relationship between separation efficiency and Particle diameter: Figure 7 shows the measured grade efficiencies of the cyclone as a function of particles diameter. It is usually expected that collection efficiency v increase with the particle diameter. However, the grade efficiency of the cyclone with cone stabilizer was always higher than the efficiency of the cyclone with

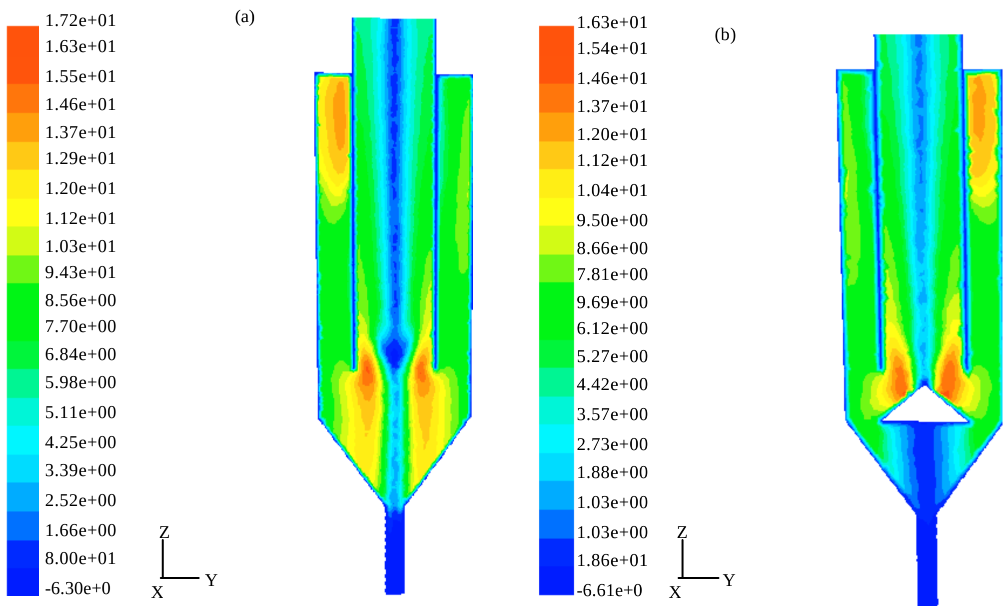

Fig. 5: Distribution of tangential velocity (anti-clockwise is positive and clock wise is negative): (a) conventional cyclone (b) cyclone with vortex stabilizer.

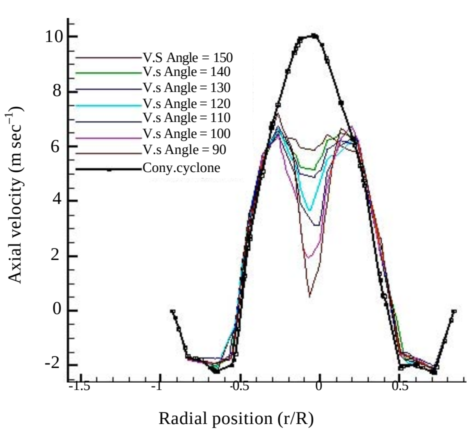

Fig. 6: Axial velocity profile along the entrance of vortex finder. Comparison between conventional and new design cyclone with various cone stabilizers angles

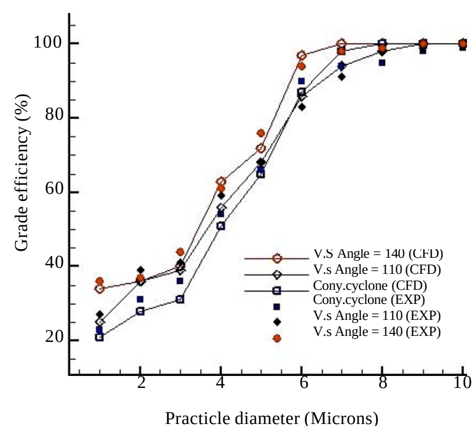

Fig. 7: Comparison of numerical and experimental cyclone grade efficiency curves for conventional cyclone and cyclone with vortex stabilizer

conventional design at the same particle diameter and especially, the cyclone with cone angle of 140 has a highest total efficiency.

These effects of cone stabilizer usage contribute to the increase in grade efficiency of the cyclone by 1-13% in the tested particle diameter range.

The relationship between overall separation efficiency and Gas velocity inlet: Figure 8 shows the measured overall efficiencies of the cyclones as a function of flow rates or inlet velocities. It is usually expected that collection efficiency increases with the entrance velocity. However, the overall efficiency of the cyclone with cone vortex stabilizer was always higher than the efficiency of the cyclone with conventional design at the same

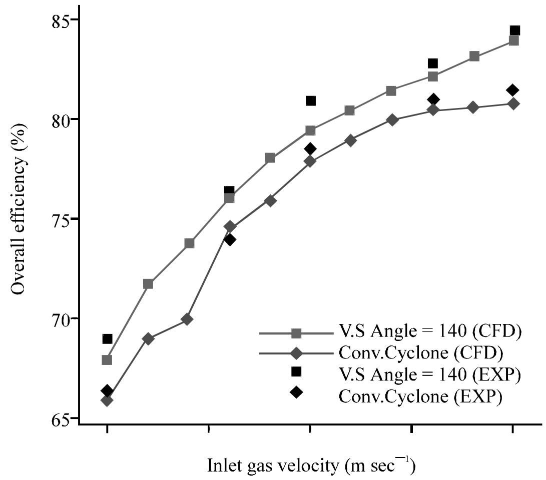

Fig. 8: Overall efficiency of cyclone at different inlet velocities

velocity and especially, the cyclone with cone angle of 140° has a highest overall efficiency.

These effects of developed vortex stabilizer contribute to the increase in overall efficiency of the cyclone by 1.3-3.8% in the tested velocity range.

CONCLUSIONS

In order to increase the cyclone separator efficiency, the effects of cone vortex stabilizer on separation performance was examined by utilization of experimentally and numerically simulations. The collection efficiency was evaluated for various cone stabilizer dimensions. The results indicate that the cone stabilizer has significant effects on reduction of turbulence intensity in the cone body of cyclone and therefore, escaping of particles to centric upward flow will be decrease. As the cone stabilizer angle is decrease, at first the total efficiency has the tendency to be higher, as it reaches a certain value (about angle of 140°), total efficiency has the tendency to be lower slightly.

ACKNOWLEDGMENT

The support of the Razi Petrochemical Complex is gratefully acknowledged.

REFERENCES

Avci, A. and I. Karagoz, 2003. Effects of flow and geometrical parameters on the collection efficiency in cyclone separators. J. Aerosol Sci., 34: 937-955.

Bernnan, M.S., M. Narashima and P.N. Holtham, 2007. Multiphase modelling of hydrocyclones-prediction of cut-size. Miner. Eng., 20: 395-406.

Bhaskar, K.U., Y .R. Murthy, N. Ramakrishnan, J.K. Srivastava, S. Sarkar and V. Kumar, 2007. CFD validation for flyash particle classification in hydrocyclones. Minerals Eng., 20: 290-302.

Chen, J. and M. Shi, 2007. A universal model to calculate cyclone pressure drop. Powder Technol., 171: 184-191.

Chuah, T.G., J. Gimbun and T.S.Y. Choong, 2006. A CFD study of the effect of cone dimensions on sampling aerocyclones performance and hydrodynamics. Powder Technol., 162: 126-132.

Cilliers, J.J., J. Diaz-Anadon and F.S. Wee, 2004. Temperature, classification and dewatering in 10 mm hydrocyclones. Minerals Eng., 17: 591-597.

Fassani, F. and L. Goldstein, 2000. A study of the effect of high inlet solids loading on cyclone separator pressure drop and collection efficiency. Powder Technol., 107: 60-65.

Grommers, H.E. and J. Krikken, 2004. Comparison of small hydrocyclones based on total process costs. Minerals Eng., 17: 581-589.

Jiao, J. and Y. Zheng, 2007. A multi region model for determining the cyclone efficiency. Sep. Purific. Technol., 53: 266-273.

Lee, J.W., H.J. Yang and D.Y. Lee, 2006. Effect of the cylinder shape of a long-coned cyclone on the stable flow-field establishment. Powder Technol., 165: 30-38.

Magwai, K.M. and J. Bosman, 2006. Fundamentals on the spigot capacity of dense medium cyclones. Minerals Eng., 20: 574-580.

Mukherjee, A.K., R. Sripriya, P.V.T. Rao and P. Das, 2003. Effect of increase in feed inlet pressure on feed rate of dense media cyclone. Int. J. Mineral Process., 69: 259-274.

Neesse, T., H. Tiefel and P. Kaniut, 2007. Volume split control of a hydrocyclone group. Minerals Eng., 20: 355-360.

Neesse, T., J. Dueck and L. Minkov, 2004. Separation of finest particles in hydrocyclones. Minerals Eng., 17: 689-696.

Qian, F., Z. Huang, G. Chen and M. Zhang, 2007. Numerical study of the separation characteristics in a cyclone of different inlet particle concentrations. Comput. Chem. Eng., 31: 1111-1122.

Sun, R. and Q.Z. Li, 2002. Simulation of strong swirling jet with different turbulence model. Power Eng., 22: 310-318.

Wang, B. and A.B. Yu, 2006. Numerical study of particle-fluid flow in hydrocyclones with different body dimensions. Minerals Eng., 19: 1022-1033.

Xiaodong, L., Y. Jianhua, C. Yuchun, N. Mingjiang and C. Kefa, 2003. Numerical simulation of the effects of turbulence intensity and boundary layer on separation efficiency in a cyclone separator. Chem. Eng. J., 95: 235-240.

Yalcin, T., E. Kaukolin and A. Byers, 2003. Axial inlet cyclone for mineral processing applications. Minerals Eng., 16: 1375-1381.

Yang, I.H., C.B. Shin, T.H. Kim and S. Kim, 2004. A three-dimensional simulation of a hydrocyclone for the sludge separation in water purifying plants and comparison with experimental data. Minerals Eng., 17: 637-641.