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The new approach to the hydrocyclone modeling using computational fluid dynamics (CFD) simulation

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ABSTRACT: This paper presents the simulation of solid particles selection in a hydrocyclone. The Fluent CFD (Computational Fluid Dynamics) software has been used for the simulation. For water flow simulation, within the hydrocyclone, the *k-ε* turbulent flow model has been used. This allows calculating the velocity, pressure and turbulence field in the hydrocyclone. The Fluent software enables simulation of the solid particles flow within the flowing liquid. Solid particles of different sizes, flowing in this hydrocyclone have been simulated. Finally the selectivity curves, as a basic characteristic of the hydrocyclone, were calculated. The obtained results give real perspective for utilization of the CFD simulations as the basic stage in industrial hydrocyclones design practice.

1 INTRODUCTION

Hydrocyclones are widely used for solid particles selection in mineral industry [1]. Hydrocyclone is a device where the selection of particles proceeds in a field of the centrifugal force action. The hydrocyclone's geometry is a cone – cylinder vessel symmetrically situated to the gravity force (see Figure 1). The centrifugal forces are generated by a flowing liquid on spiral trajectory in the motionless vessel. The spiral flow is generated by tangential entry of the suspended solids. The physical differences of size and specific gravity allow the separation of particles in the hydrocyclone. Inside the hydrocyclone, two rotating streams are formed. One stream rotates close to the hydrocyclone's wall and flows down with bigger and heavy particles to the underflow. The second stream rotates near the centre and flows up with small and lightweight particles to the overflow. The main characteristic of the hydrocyclone's performance is a selectivity function *s* (*d*). This curve presents the percentage amount of given particles size flowing to the underflow as a function of particle sizes *d*. The basic parameter, the cut size d_{50}, represents the size of such particles that 50% of them flow out to the underflow. The selectivity curve is a function of several geometrical parameters of the hydrocyclone, composition of a liquid-solid suspension and a flow rate. There are some semi-theoretical equations which attempt to describe this function [2].

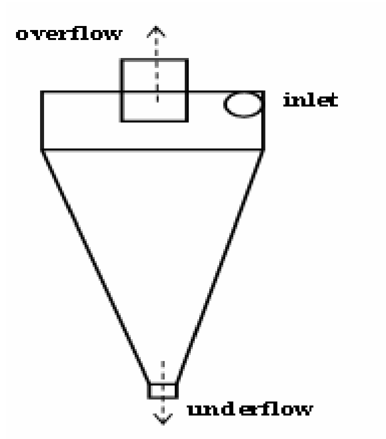


Figure 1. Hydrocyclonens cheme

2 TURBULENCE FLOW MODELS

Turbulent flows are most common, the most important and the most complicated of the fluid motion. At last three decades the great development in turbulent flow modeling and computing has been done. Basing on the theoretical analysis and experimental data several models have been studied like: Spalart-Allmaras model, *k* - *ε* model, *k*- *ω* model, Reynolds Stress Model (RSM) and Large Eddy Simulation (LES) model. The *k-ε* turbulent flow model has been used for calculations, which are presented in this paper. The standard $k-\varepsilon$ model is a semi-empirical model based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε) [3, 4, 5].

In Eulerian frame, the turbulent flow field may be specified by velocity vector **U** with three orthogonal components (u_1, u_2, u_3). In Reynolds averaging, each velocity component may be split into the mean (ensemble-averaged or time-averaged) and fluctuating (turbulence) components (eq. (1)).

$$u_i = \overline{u}_i + u'_i \qquad (1)$$

where $\overline{u}_i$ and u'_i are the mean and fluctuating velocity components ($i = 1,2,3$).

Besides the velocity U, the turbulent flow field may by specified by pressure p, density ρ and temperature T. For the determination of these quantities the following differential equations are requisite:

- conservation of momentum

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right]+\frac{\partial}{\partial x_j}\left(-\rho\overline{u'_i u'_j}\right) \qquad (2)$$

where μ is the laminar viscosity, δ_{ij} is the Kronecker delta function and the last element of this equation represents the Reynolds stresses which are relate to the mean velocity gradients:

$$-\rho\overline{u'_i u'_j} = \mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\left(\rho k+\mu_t\frac{\partial u_i}{\partial x_i}\right)\delta_{ij} \qquad (2a)$$

where μ_t is the turbulent viscosity

- continuity of flow

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \qquad (3)$$

- energy equation

$$\frac{\partial}{\partial t}(\rho E)+\rho\frac{\partial}{\partial x_i}(\rho u_i E)=\frac{\partial}{\partial x_j}\left(\lambda\frac{\partial T}{\partial x_j}+u_i\delta_{ij}\right) \qquad (4)$$

where E is the total energy and λ is the thermal conductivity

- transport equations for the turbulence kinetic energy - k

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M \qquad (5)$$

- transport equations for the turbulence energy dissipation - ε

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_K+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad (6)$$

where: G_K represents the generation of turbulence kinetic energy due to the mean velocity gradients, G_b is the generation of turbulence kinetic energy due to buoyancy, Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are constants. σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively.

- equation for the turbulent (or eddy) viscosity - μ_t

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \qquad (7)$$

where C_μ is a constant.

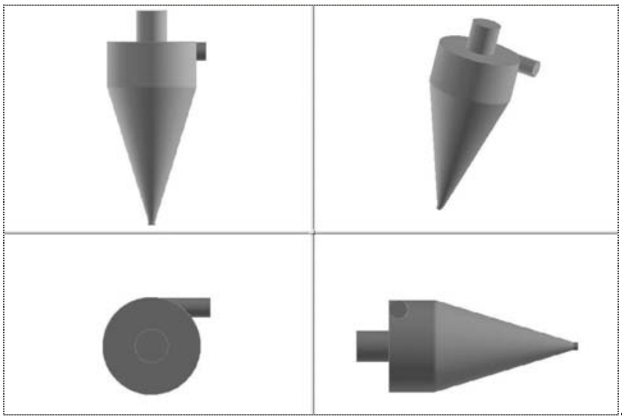
The model constants $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ, σ_k and σ_ε have the following default values

$$C_{1\varepsilon}=1.44, \quad C_{2\varepsilon}=1.92, \quad C_\mu=0.09, \quad \sigma_k=1.0, \quad \sigma_\varepsilon=1.3 \qquad (8)$$

These default values have been determined from experiments with air and water for fundamental turbulent shear flows including homogeneous shear flows and decaying isotropic grid turbulence. They have been found to work fairly well for a wide range of wall-bounded and free shear flows.

3 CFD SIMULATION AND RESULTS

For CFD simulation the commercial software GAMBIT and FLUENT has been used. The GAMBIT software has been used for the hydrocyclone's geometry and the mesh preparation. Fig. 2 shows the geometry of the hydrocyclone prepared in Gambit software. Then, the three-dimensional tetrahedral-hybrid mesh was constructed and a total of 960,000 mesh cells were used. Then the Fluent software was used for water flow simulation inside the hydrocyclone. The 121700 Pa pressure value was chosen as boundary condition in inlet. After about 8000 iteration the steady flow was accomplished. In this steady flow the mass flow rate in inlet was 27.2 kg/s (mean velocity 3.43 m/s) and it separated into overflow (25.2 kg/s) and underflow (2.0 kg/s). The simulation gives the entire profiles of flow values like: velocity, pressure, turbulence, etc. In Figure 3, the examples of these profiles in the hydrocyclone's vertical cross section are shown. The water flow can also be presented on the path lines that are shown in Figure 4.



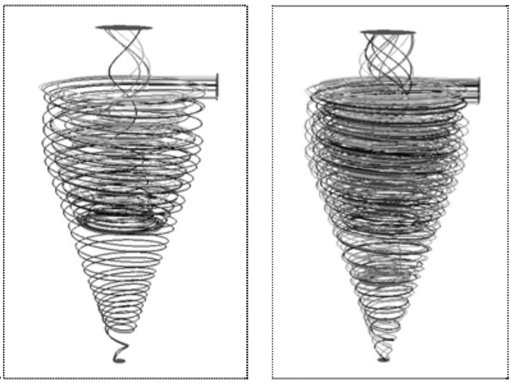


Figure 2. Hydrocyclone geometry prepared in Gambit.

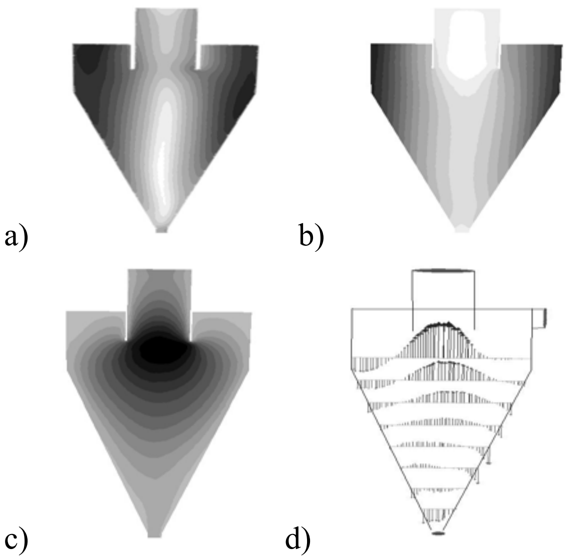


Figure 3. Contours of a) velocity b)static pressure, c)turbulent kinetic energy, d)velocity vertical vectors.

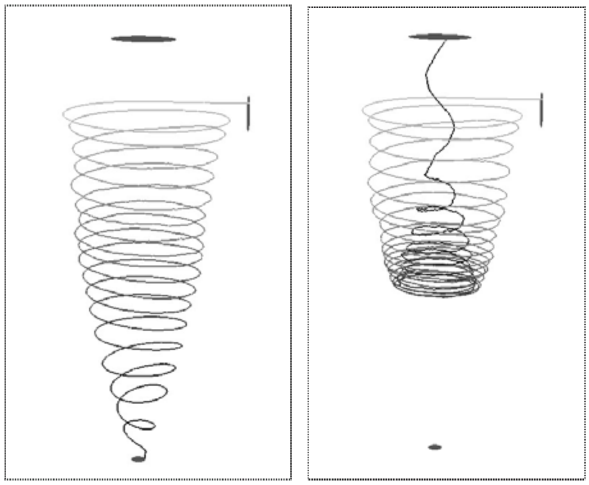
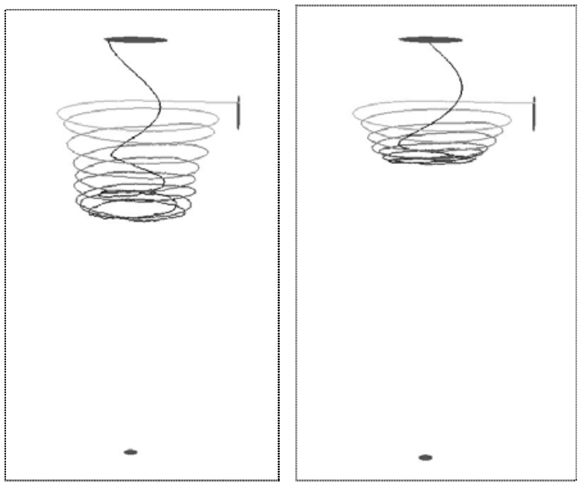


Figure 4. Examples of the water flow path lines.



d = *100 μm* d = *90 μm*
d = *80 μm* d = *5 μm*

Figure 5. Examples of the particles trajectory.

The next step consisted in solid particles' flow simulation inside the hydrocyclone with flowing water. For a solid, the dolomite particles (density – 2872 kg/m^3) from size 5 μm to 500 μm were chosen. The particles flowed into the hydrocyclone's inlet with the same velocity as water. The particles trajectory is calculated by force balance equates and turbulent dispersion of particles where the Discrete Random Walk (DRW) model is used. The examples of solid particles' trajectories, for different size are shown in Figure 5. Finally it was possibly to simulate the selectivity curve for solid particles. In Figure 6 the simulated selectivity curves with and without turbulent dispersion of solid particles are shown.

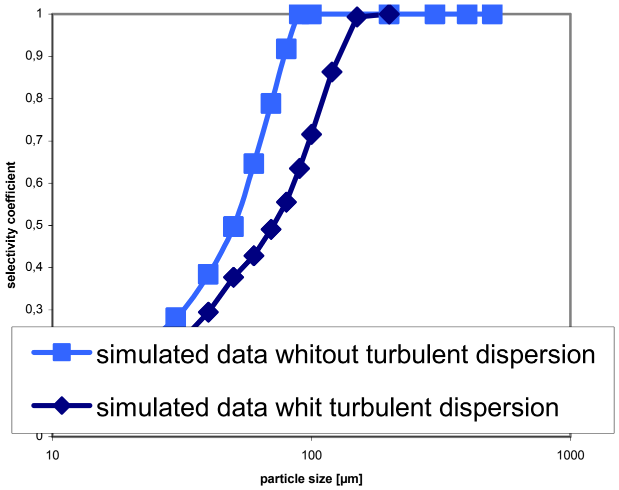


Figure 6. Simulated separation curves without and with turbulent dispersion.

4 CONCLUSIONS

The modern CFD Fluent software is applied to the flow simulation and solid particles selection in the hydrocyclone. This simulation allows achieving the whole three dimensional profiles of the water flow values like: velocity, pressure, turbulence, etc. Finally, the solid particles' selection can be simulated in this hydrocyclone.

The obtained results establish the primary step for prediction of solid particles' selection in hydrocylones used in mineral industry. The next step should be the simulation of fluid as a heterogeneous mixture (water + solids) and solid particles selection in this specific hydrocyclon's mixture. This should resemble real industrial conditions as closely as possible. Anyway, this prediction for the industrial application will need experimental data for verification of the simulated results and the other way the experimental data are essential for choosing the optimal CFD model and its parameters.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Kraipecha W., Chenb W., Parmab., F.J., Dyakowski T. *Modeling the fish-hook effect of the flow within hydrocyclones*, International Journal of Mineral Processing vol. 66 (2002) pp. 49-65.

Nowak E., Stęgowski., Tora B., Kurzac M.: *Computational fluid dynamics (cfd) simulation for solid flow and selection in a hydrocyclone,* XX Int. Mining Congress, Teheran, Iran (2005)

Pope B. S., *Turbulent Flow*, Cambridge University Press, 2000

Salas M.D., Hefner J.N., Sakell L., *Modeling Complex Turbulent Flows*, Kluwert Academic Publishers, 1999

Stegowski Z. and Leclerc J-P., *Determination of the solid separation and residence time distributions in an industrial hydrocyclone using radioisotope tracer experiments*, International Journal of Mineral Processing vol. 66 (2002) pp. 67-77.

Wilkes J.O. *Fluid Mechanics for Chemical Engineers*, Prentice Hall PTR, New Jersey, 1999.