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Fluid Dynamics and Simulation Study of Particles Inside of a Hydrocyclone using Comsol

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The parameters that define the performance of the hydrocyclone in mineral size reduction circuits are the profile of selectivity of the size of ore pulp in discharge and the overflow from hydrocyclone, along with the velocity field of the pulp to the interior of this reactor. The dynamical behaviour of the hydrocyclone and the particle size of the final product in 3D using COMSOL Multiphysics were studied in this article. The fluid is governed by the continuity and the conservation of the momentum equations, in addition to the k-ε turbulence model. Studies were performed on a hydrocyclone of 75 [mm], and a flow of pulp of 4.88% solids by weight. The simulation presented results suitable for particle sizes greater than 17.74 [µm], within a range of 9 to 35.5 [µm]. For lower sizes, selectivity curve presents problems since the turbulence model is not suitable for modelling the ascending secondary vortex in the hydrocyclone.

1. Introduction

One of the most important aspects of the circuits of size reduction on grinding is the classification efficiency of the hydrocyclone, which has the function of separating sizes in given slurry. The hydrocyclone is a mechanical device that does not include moving parts or engine; but it requires external power for operation, normally provided by a centrifugal pump in continuous operation. A hydrocyclone that process mineral slurries, i.e., solid - liquid mixtures, is constituted by a cylindrical body, on the top there is a disc crossed by an outlet cylinder called overflow or vortex, which separates most of the liquid and fine material fed. The bottom is coupled with a conical part of smaller diameter corresponding to the discharge or apex, where the coarser particles are discharged. The feed throat, which is rectangular or circular; It is located at the top of the cylinder, and the feed inlet can be envelope or tangential. Due to the tangential inlet feed of slurry, inside of the device is promoted the formation of a descending vortex product of the gravitational field. In the centre of the hydrocyclone, an ascending vortex known as low pressure air core, which generates a radial distribution of particle sizes product of the drag and centrifugal forces formed.
Inefficiencies in the separation cause 2 types of problems: at the apex, the presence of fine-grained ore inducing over-grinding, which decreases ore recovery of interest, due to the difficulty to recover in the flotation process. While in the case of overflow, large particles do not allow complete release of the ore. The efficiency of the separation process of the hydrocyclone, can be seen in Figure 1.

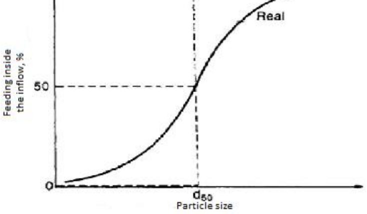

Figure 1: Efficiency of the separation of the hydrocyclone.

For these reasons the trajectory of particles will be studied in a conventional hydrocyclone, using the "Particle Tracing for Fluid Flow" tool from fluid flow module from Comsol Multiphysics, version 3.3 (COMSOL, 2013).

2. Theoretical Basis

2.1 Formulation turbulence model

The objective of the momentum transfer equations is the determination of the velocity field and pressure to which it is subjected fluid flow, either liquid or gaseous, in a work domain. The momentum transport will be represented by the Navier-Stokes equations Eq(1).

$$\rho\frac{\partial U}{\partial t} - \nabla\cdot(\eta+\eta_T)(\nabla U + (\nabla U)^T) + \rho U\cdot\nabla U + \nabla p = F \quad (1)$$

And the continuity equation is defined by the equation Eq(2).

$$\nabla\cdot U = 0 \quad (2)$$

Eq(1) includes the following quantities: ρ is the density kg/m³, η is the viscosity Pa·s, u is the velocity vector m/s, p is pressure Pa, F is the volume force vector N/m³. These equations can be extrapolated to turbulent flow simulations. An alternative to simplify this problem is to consider the average equations, using the statistical regularity. For incompressible fluids, the velocity component is determined as follows Eq(3).

$$u_i = \overline{u_i} + u_i' \quad (3)$$

Where u_i is the velocity field over a given time interval, $\bar{u}_i$ is the average time component and u'_i is a component which fluctuates. Then, the Navier - Stokes modified is written as Eq(4) and continuity as Eq(2).

$$\rho\frac{\partial U}{\partial t} - \nabla\cdot\eta(\nabla U + (\nabla U)^T) + \rho U\cdot\nabla U + \nabla\overline{(\rho u'\otimes u')} + \nabla p = F \quad (4)$$

Where U is the average velocity and $\overline{u'\otimes u'}$ is the term which represents the interaction between the velocity fluctuations, and is called Reynolds stress tensor. The only difference from the original Navier-Stokes equation is the insertion of Reynolds stress tensor, which is considered as the contribution of turbulent fluctuations in the flow of convective momentum. Finally, is required a closure scheme, which is to impose assumptions to simulate the flow completely. A well-known and recurrent scheme closure is the k-ε model, consisting of two additional transport equations solved: the turbulence kinetic energy, k, and the dissipation rate of turbulence energy, ε. Momentum transport is quantified using Eq(5) with Eq(6).

$$\overline{u'\otimes u'} = -\nu_T\cdot(\nabla U + (\nabla U)^T) \quad (5)$$

And.

$$\nu_T = \frac{\eta_T}{\rho} = C_\mu\frac{\mathrm{k}^2}{\varepsilon} \quad (6)$$

Where ν_T is the turbulent kinematic viscosity, η_T the dynamic viscosity turbulent and C_μ is a constant model with a value of 0.09. This closes the system for the conservation of momentum and continuity equations.

2.2 Formulation of particle dynamics

The drag force is a mechanical force, generated by the interaction of a rigid body and a fluid, and is defined as follows Eq(7).

$$F_D = C_D\left(\frac{1}{2}\rho v^2 A\right) \quad (7)$$

F_D is the drag force, C_D is the drag coefficient, ρ is the fluid density, v is the object/fluid relative velocity, and A is the characteristic area.
Considering a solid spherical particle (Brown P. and Lawler D., 2003), where d_p is the diameter of the particle and r_p is the ratio of the particle, the characteristic area is defined as Eq(8).

$$A = \frac{\pi {d_p}^2}{4} = \pi {r_p}^2 \quad (8)$$

According to Buckingham's theorem (Dlamini, M.F. et al, 2005) C_D depends on the Reynolds number Eq(9).

$$Re_p = \frac{d_p v\rho}{\eta} \quad (9)$$

Re_p is the particle Reynolds number, and the characteristic length is defined as d_p.

The following Eq(10) describes the total force that a fluid exerts on an immersed spherical particle, according to Khan and Richardson (Ipate, G., Casandroiu, T., 2007):

$$F = \left(\frac{1}{2}\rho v^2 A\right)\left(2.25{Re_p}^{-0.31} + 0{,}36{Re_p}^{0.06}\right)^{3.45}, \quad 0.01 < Re_p < 3 \cdot 10^5 \tag{10}$$

And for turbulent flow, the relative velocity is defined as Eq (11).

$$v = \left(U - U_p\right) \tag{11}$$

Where U is the mean velocity vector of the fluid and UP is the mean velocity vector of the particle.
Then, replacing both.

$$F = \pi {r_p}^2 \rho \left(U - U_p\right)^2 \left(1{,}849{Re_p}^{-0.31} + 0{,}293{Re_p}^{0{,}06}\right)^{3.45} \tag{12}$$

Thus, through Eq(12), the force exerted by the system on the particle, and its tendency to abandon the reactor by the discharge, or the overflow, will be determined.

2.3 Formulation the density and viscosity of the pulp

Since Eq(12) is dependent on the density of the pulp, the Eq(13) will be used:

$$\rho_{pulpa} = \frac{\rho_s \cdot \rho_l}{\rho_l \cdot C_p + \rho_s \cdot \left(1 - C_p\right)} \tag{13}$$

ρ_s and ρ_l are the densities of the solid and liquid, respectively, and C_v and C_p are percentages by volume and weight, respectively.
It is considered that the fluid continues to behave as Newtonian and a correction expression Eq(14) is used for the viscosity of the suspension, proposed by Hsieh (Hsieh, Kuo-Tai, 1998).

$$\frac{\eta_{pulpa}}{\eta_{agua}} = 1{,}0 + 2{,}5 \cdot C_v + 10{,}05 \cdot (C_v)^2 + 0{,}00273 \cdot e^{(16{,}6 \cdot C_v)} \tag{14}$$

3. System modelation

In order to know the behaviour of the profiles of the velocity components: tangential, axial and radial, graphs are used from the study of Concha (Concha, F., 2006). On the other hand, the study of Romero (Romero, J. et al, 2004) proposes a model applied to two different hydrocyclones: AKW-100 and Hsieh, the latter being the one of interest, since it presents the selectivity curve of Figure 2.
Working with a cylindrical air core simplifies the problem, but it must be considered that the choice of radius can affect feed pressure and flow separation, and thus the construction of the classification curve.

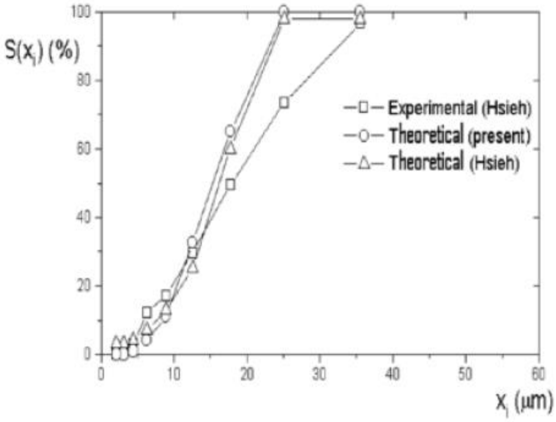

Figure 2: Selectivity or partition curve for hydrocyclone of 75 [mm] (AKW-100).

Finally a core radius of 6 [mm] was drawn, close to that determined by Romero (2004).
For the present paper the selection of only 4 simulations is presented: Sim1, Sim2, Sim3 and Sim4. The conditions for the type of fluid used, presented in Table 1 and the conditions of each of them, can be seen in Table 2.

Table 1: Operating conditions of hydrocyclone

Operation Parameters	Slurry	Water	Solid
ΔP,Pa	60,000	60,000	-
ρ, kg/m³	1,031	1,000	2,650
η, pa·s	1.0548	1.0	
C_v, %	1.9		
C_p, %	4.88		

Table 2: Conditions of four simulations carried out, to represent the experimental partition curve of Hsieh.

Simulation	Fluid	k-ε Param.	Tuning Param.	Core	Axial Velocity	N° Particles
Sim1	Water	k_0=1, ε_0=25	$\delta_{sd,T}$=0.1,δ_{sd} =0.1	No	v_w =52 m/s	15
Sim2	Slurry	k_0=1, ε_0=25	$\delta_{sd,T}$=0.1,δ_{sd} =0.1	Yes	v_w =52 m/s	15
Sim3	Slurry	k_0=1, ε_0=25	$\delta_{sd,T}$=0.25,δ_{sd} =0.25	Yes	v_w =60 m/s	15
Sim4	Surry	k_0=1, ε_0=25	$\delta_{sd,T}$=0.25,δ_{sd} =0.25	Yes	v_w =60 m/s	450

A mesh sensibility analysis was done out to define the mesh. This analysis consisted in various simulations with identical configurations and different meshes. Each simulation used a thinner mesh until no difference was found in the results.
The mesh used for the computational fluid dynamics simulation is shown in Figure 3.
The mesh was refined at the walls, in order that the minimum element quality was 0.001218; 1,275 edge elements and 27 vertex elements. The final mesh has 403,424 tetrahedral elements, 2,850 pyramid elements and 78,494 hexahedral elements.

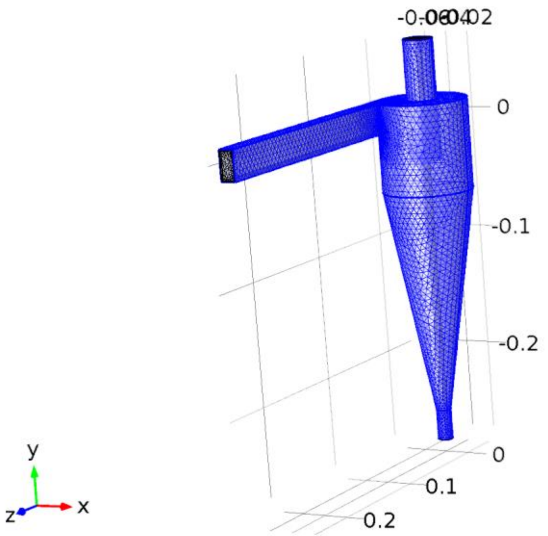

Figure 3: Mesh used for the computational fluid dynamics simulation.

4. Results and Discussions

In Sim1 is simulated the behavior of water inside a hydrocyclone by the k-ε model, responding as if it were a cord-type operation; That is, in the underflow all the fluid falls without presence of an upward whirlwind in the core as Hsieh (1998) shows. In addition, Figure 4 shows the behavior of the partition curve (selectivity) for particle size between 9 and 35.5 [μm], indicating the percentage of particles for each size reported in the underflow. Sim1 presents results far from the experimental curve obtained by Hsieh, especially for particle sizes below 17.74 [μm].

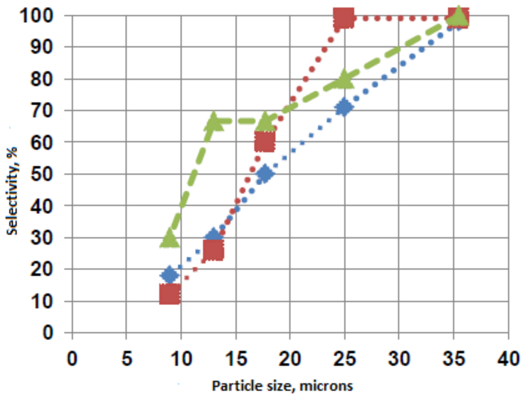

Figure 4: Selectivity. Hsieh experimental curve (blue), Hsieh theoretical curve (red) and adjusted simulation proposed in the model without presence of an upward whirlwind in the core (green).

This indicates that a large fraction of fine particles flow through the underflow, due to the absence of the upward vortex that would report it in the overflow. Due to the above, Sim2 is made, which incorporates a defined radio core, without subdomain, but its wall complies with the fluid-air interface condition, that is, the movable wall with exits. The particles that reach the wall of the core, and those that flow in the overflow will be considered as reported in this, since it is highly probable that the finer particles reach the core. The movement of the core wall is considered only upward (y-axis), i.e., it rises without rotating on its axis (y). This is assumed because of the difficulty of incorporating the tangential velocity of the core wall in cartesian coordinates.

In relation to Sim1, in Sim2 a smaller percentage of fine particles is coming out through the underflow, i.e., the curve is more adjusted to Hsieh curve for particle sizes smaller than 17.74 [μm].

To set the Sim2 data to the Hsieh curve, Sim3 is performed. Table 2 shows the parameters adjusted to obtain the results of Figure 5. However, there remains a problem, the initial position of a particle in the feed determines the trajectory of the particle; That is, depending on its position, can be reported in the overflow or in the underflow, according to the size of the latter. For this reason, 15 representative particles establish the partition curve, by means of Sim4 that is presented in figure 6.

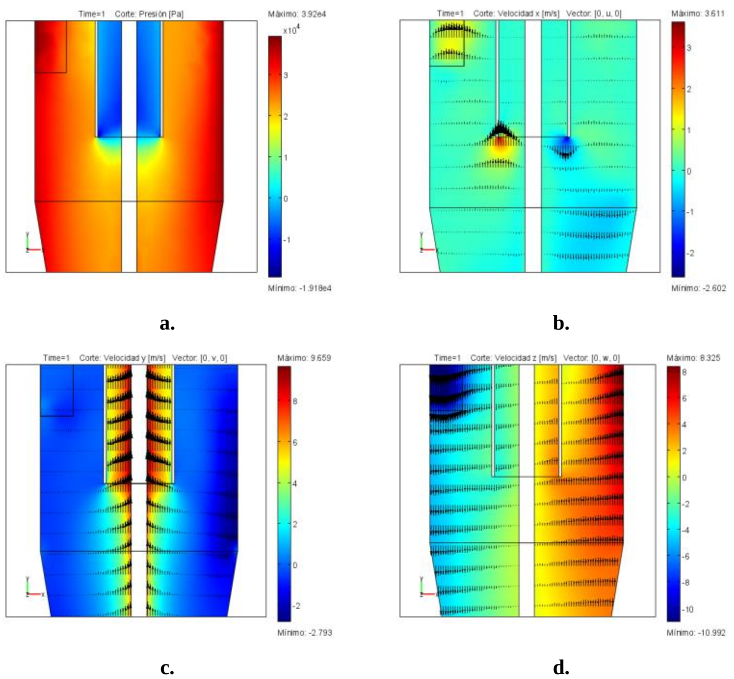

Figure 5: Pressure field and velocity field in the x-y plane according to the Sim4, where (a) Pressure, (b) Radial velocity, (c) Axial velocity and (d) Tangential velocity. Front view of the top of the hydrocyclone.

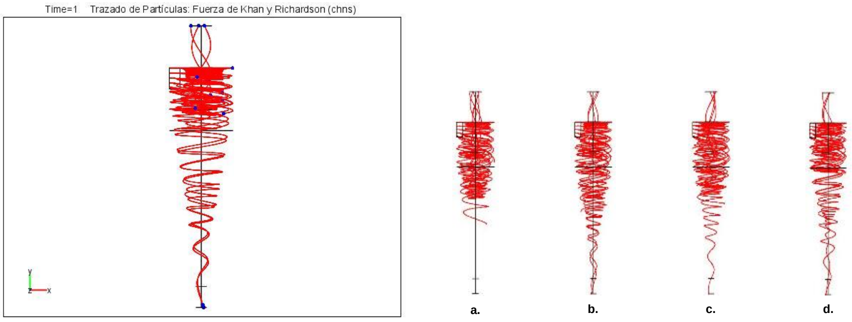

Figure 6: Trajectory of 15 particles of 20 [µm] in water, considering the drag coefficient of spherical particles proposed by Khan and Richardson. Turbulence parameters a: ε_0 = 0.1[m²/s³] y k_0 = 0.1[m²/s²], b: ε_0 = 1[m²/s³] y k_0 = 0.1[m²/s²], c: ε_0 = 300[m²/s³] y k_0 = 1[m²/s²], d: ε_0 = 300[m²/s³] y k_0 = 10[m²/s].

It is observed that the modification of the parameters ε_0 and k_0 does not alter the behavior of the fluid in the axial component of velocity, but it changes the trajectory of the particles.

5. Conclusions

It hydrocyclone for the particle size separation was modelled using the turbulence model k-ε under transient analysis, determined that after one second the steady state is reached.
The turbulence model does not adequately represent the secondary whirlpool in a hydrocyclone, yielding an approximation to the experimental Hsieh selectivity curve for particle sizes greater than 17.74 [µm], between a range from 9 to 35.5 [µm].
The developed model can simulate the actual behaviour of the fluid dynamics of particles inside the hydrocyclone, considering a cylindrical core without physical properties, with a condition of movable wall with exits and with an ascending velocity.
A good representation of the velocity profiles and the partition curve with the experimental data obtained by Hsieh is obtained with a core of radius of 6 [mm], operating with 450 particles per size, using tuning parameters δ_{sd}, T = 0.25 and δ_{sd} = 0.25, and an axial core wall velocity v_w = 60 m/s.
The model presents profiles of tangential, axial and radial velocity, and pressure according to the fluid-dynamics of the hydrocyclone.
The simulated results using the turbulence model k - ε allow to investigate the fluid flow behaviour and trajectory of the particles in the size separation process inside the hydrocyclones.

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