THE EFFECT OF EROSION CAUSED BY SOLIDS PARTICLES IN THE HYDROCYCLONE PRESSURE VESSEL

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Abstract. Hydrocyclones are separators widely used in pulp and paper mills for separating dispersed solid particles mainly sand from the feed system with chips of wood. This equipment has simple design and low cost of maintenance. Therefore they are also used in many engineering process such as dryers, reactors, mining industries. A correct understanding of the hydrocyclone flow and pressure fields is required to evaluate the effect of erosion caused by solids particles in the hydrocyclone pressure vessel in special attention on the perforated insert. The solids particles of sand in the liquid that is used to carry the chips of wood ahead are separated according to density, size and shape due gravitational forces which drive the separation in a hydrocyclone as pressure energy is converted into rotational momentum. The feed enters tangentially on the upper nozzle of the cylindrical section and it creates a vortex around the axis of the hydrocyclone. The CFD is used to solve and analyze complex problems that involve fluid flows using numeric methods and equations. This work presents a Computational Fluid Dynamics (CFD) model of hydrocyclone sand separator. The modeling and simulation is carried out using commercial software available ANSYS-CFX (release 12.1) to analyze the flow pattern, pressure drop, velocity and erosion phenomena inside of hydrocyclone. The results using different turbulence models Shear Stress Transport (SST) with curvature correction and RNG k-ε are compared with the experimental results of erosion observed in pulp and paper mills. The CFD techniques present strong resource to predict the swirling field flow and erosion phenomena on the hydrocyclone turbulence models simulation.

Keywords: Hydrocyclone, CFD, SST, RNG k-ε, Erosion Rate, Turbulence Model.
1. INTRODUCTION

The first U.S Patent hydrocyclone design was in 1891 granted by [2] Bretney (No. 453, 105). The hydrocyclone became more popular in different industries after 1945. This device has been used very often specially in oil and chemical industries and has several applications in other industrial segment such as, thickening, liquid-liquid separation, fluids clarification, solids removal.

Hydrocyclones are gravity separators of relatively simple mechanical design and it has been widely used in separation and classification. There are no moving parts. In order to function, they require an internal vortex flow as well as a difference in densities between the liquor and the particles to be separated. In the pulp and paper industries the hydrocyclones are used in different stages of the mill. The sand separators as they are called in the pulp and paper mills, the first and most important stage it is in the cooking area where the sand are being fed within chips of wood to be cooked into the pressure vessel.

Typically the hidrocyclone concept consists in a cylindrical section with a central pipe, vortex finder, connected to the outlet. The inlet is attached to the top of the cylindrical section. The conical section is located the underflow where the particle solids will be removed from the process. They have simple design and operation, high capacity and low maintenance and operating costs and are relatively small [4] Bradley, 1965; [14] Svarovsky, 1984.

In the pulp and paper industries the hidrocyclones that are used to do sand separation have the conical bottom section a perforated insert in order to avoid plug with fibres and piece of wood chips and a protection cone to keep the system hydraulically pressurized. As the name implies, the sand separator removes excessive sand from the system. This can increase the life of many equipment, valves and pipes. The liquor enters the separator tangentially and centrifugal forces carry the sand to the periphery. Sand accumulates and settles to the bottom. Here it passes through the perforated insert and is removed from the system. The perforated insert is subject to severe wear due to sand erosion.

Even being very simple equipment for separation and or classification, the two or more phase turbulent flow field start to be a quite complex understanding and many factors can affect your performance during the operation. Also the geometry has influence on performance.

Several authors have attempted to calculate particle trajectories in the hydrocyclone. The cylindrical section is usually treated as a preliminary separating zone and the particles injected near the wall can be dispersed radially. The main zone for the separations is the conical section.


Recently the CFD simulations and techniques has gained popularity in process simulation, optimization and design providing excellent understanding of the hidrocyclone performance. The very first CFD simulation was done by [3] Boysan et al. (1982). On this simulation was used the k-ε turbulence model and he assumed that the turbulence was isotropic due only one scalar velocity fluctuation is modelled. Some authors suggest that the renormalization group (RNG) k-ε model with a swirl correction to improve the precision of simulations [6] Fraser et al., 1997; He et al., 1999; [15] Schuetz et al., 2004 instead k-ε because this model is not suitable to simulate a turbulent flow with high swirl. However, the RNG k-ε is also limited for modelling a hydrocyclone.

Therefore the turbulence model is one of the most important parameter in hydrocyclone flow due the very complex anisotropic models such as Reynolds Stress Model (RSM). Besides of RSM
model, recently Large Eddy Simulation (LES) has been used and this approach has eliminates the explicit empiricism that is imposed in the $k-\varepsilon$ model (Delgadillo and Rajamani, 2007).


The turbulence swirling flow with solids particles can be very abrasive and cause erosion of the parts of the internal wall and in the perforated insert of the sand separator. The sand particles is the most predominant factor causing deterioration of the surface due the impact produced by abrasive particles suspended in the liquid, therefore this erosion process turns out to be purely mechanical. During residual deformations, a certain volumetric part of the surface layer will be separated from the bulk mass of a component, leaving a trace which is characterized by significant roughness caused by action pattern. Therefore, the main goal in the design is also to have a good resistance to wear and not only to provide better hydrocyclone performance.

2. MATHEMATICAL MODELLING

2.1 Turbulence Model

Based on morphologies of phases, the choice of modelling approach can be disperse phase when it occupies disconnected regions of space or continuous phase when it is connected in space. Also in some cases such as multiphase flows there is possibility to have disperse–continuous flows with more than one disperse phases and or continuous-continuous flow.

In this study the simulation was performed utilizing the dispersed multiphase flow with Lagrangian approach due small fraction (0.0042%) of sand in the process. The Lagrangian approach deals with dispersed flows and detailed information on particles position, velocity, trajectory and residence time is available. Also the impact of particles on solid walls can be modelled naturally. Therefore this model is ideal for studying erosion problems. On other hand many particle tracks are needed to give statically meaningful and the computation can be long and expensive.

The RNG $k-\varepsilon$ model (called renormalization group theory) was derived using a rigorous statistical technique. On this model it is included additional term in its $\varepsilon$ equation that improves the accuracy for rapidly strained flows. The derivation results in a model with constants different from those standard $k-\varepsilon$ models. The model can be obtained from the following equations:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k v_j)}{\partial x_j} = \frac{\partial}{\partial x_j} (\alpha_j \mu_{eff} \frac{\partial k}{\partial x_j}) + G_k + G_b - \rho \varepsilon - Y_M + S_k
\]

Equation (1)

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon v_j)}{\partial x_j} = \frac{\partial}{\partial x_j} (\alpha_j \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_H G_b) - C_{2\varepsilon} \frac{P}{k} - R_\varepsilon + S_\varepsilon
\]

Equation (2)

The equations (1) and (2), $G_k$ and $G_b$ represents the turbulence kinetic energy generations due to mean velocity gradients and buoyancy. The contribution of fluctuation dilatation it is
represented by $Y_m$ in compressible turbulence. The inverse effective Prandtl numbers for $K$ and $\varepsilon$, are the quantities of $\alpha_k$. User-defined source terms as $S_k$ and $S_\varepsilon$ and $C_1\varepsilon$ and $C_3\varepsilon$ are constants.

One of advantage using the RNG $k$-$\varepsilon$ model is the effect of swirl or rotation by modifying turbulent viscosity is provided due an option taken in account of functional form:

$$
\mu_t = \mu_{t0} f(\alpha, \Omega, \frac{k}{\varepsilon})
$$

Equation (3)

Where $\mu_{t0}$ is the turbulent viscosity calculated without the swirl modification, $\Omega$ is the characteristic of the swirl number, and as is a swirl constant that can assume different values. In the equation (2) there is the variable $R_e$ that show the main difference between the standard and RNG $k$-$\varepsilon$ models.

The Shear-Stress Transport (SST) turbulence model was developed by Menter (1994) to give high accurate results under adverse pressure gradients by the inclusion of transport effects into the formulation of the eddy-viscosity. This was a good combination of $k$-$\omega$ in the inner boundary layer and $k$-$\varepsilon$ model in the outer region of and outside of the boundary layer. Also it was included a damped cross-diffusion term in the $\omega$ equation. As mentioned before some features make the SST $k$-$\omega$ more accurate and more reliable when used for a wider class of flows than the standard $k$-$\omega$.

Below can see the SST $k$-$\omega$ model has similar form to the standard $k$-$\omega$ mmodel:

$$
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left( I_k \frac{\partial k}{\partial x_j} \right) + \frac{\partial}{\partial x_j} \left( I_\omega \frac{\partial \omega}{\partial x_j} \right) + G_k - Y_k + S_k
$$

Equation (4)

$$
\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x_j} (\rho \omega u_j) = \frac{\partial}{\partial x_j} \left( I_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + D_\omega + S_\omega
$$

Equation (5)

Where $G_k$ means the generation of turbulence kinetic energy due to mean velocity calculated from $Gk$ and $G\omega$ represents the generation of $\omega$, calculated from the standard $k$-$\omega$. The $\Gamma_k$ and $\Gamma_\omega$ represent the effective diffusivity of $k$ and $\omega$, respectively. $Y_k$ and $Y_\omega$ represent the dissipation of $k$ and $\omega$ due to turbulence. $D_\omega$ represents the cross-diffusion term. $S_k$ and $S_\omega$ are user-defined source terms.

2.2 Erosion Model

Typically the particle erosion and accretion rates can be calculated at wall boundaries on the following model equations. The erosion rate defined as (Fluent, 2006)
Where \( C(dp) \) is a function of particle diameter, \( \alpha \) is the impact of the particle path with the wall face, \( f(\alpha) \) is a function of impact angle, \( v \) is the relative velocity, and \( A \) is the area of the cell face at the wall. The three functions \( C, f \) and \( b \) can be defined as boundary conditions at the wall. However, the default values are not updated to reflect the material being used. These parameters have to be updated for different materials. Also the impingement angle function can be used as the following model (Finnie, 1960; Mazure et al., 2004)

\[
f(\alpha) = \sin(2\alpha) - 3\sin^2(\alpha) \quad \text{for } \alpha \leq 18.43^\circ
\]

Equation (7)

\[
f(\alpha) = \cos^2(\alpha)/3 \quad \text{for } \alpha > 18.43^\circ
\]

Equation (8)

And accretion rate is given by

\[
R_{\text{accretion}} = \sum_{p=1}^{N} \frac{\dot{m}_p}{A}
\]

Equation (9)

To calculate the erosion rate from equation (6), the diameter function and velocity exponent function are adopted as 1.8E-09 and 1.73 (Fluent, 2006; Edwards et al., 2000; Edwards et al., 2001). The CFD model records the number, velocity, mass and the impact angles the various particles for each of the grids that form the internal geometry of the hydrocyclone. The erosion rate of the hydrocyclone walls is determined using equations (6), (7) and (8). Many parameters affect the erosion rate, such as flow rate, design of the inlet, sand concentration, geometry and dimensions of the hydrocyclone and slurry properties.

3. NUMERICAL METHOD

In CFD, the Finite Volume Method (FVM) is one of the most versatile techniques used. Typically the main feature of the FVM is that the resulting solution satisfies the conservation of quantities such as mass, momentum, energy, and species. In any control conservation this can be satisfied, also for the whole computational domain and for any number of control volumes. The integral balances are exact solutions even when with the coarse grid.

In this paper the equation system is solved by commercial code ANSYS-CFX (release 12.1), which uses the finite volume method. For this study it was collected sample of sand in mill in order to do the distribution in different band as follow on the table 1.
Table 1. Sand particle size distribution @2650 kg/m³ density

<table>
<thead>
<tr>
<th>Band</th>
<th>micron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>174,700</td>
</tr>
<tr>
<td>Band 2</td>
<td>220,200</td>
</tr>
<tr>
<td>Band 3</td>
<td>329,600</td>
</tr>
<tr>
<td>Band 4</td>
<td>463,400</td>
</tr>
</tbody>
</table>

The fluid used on the process was Caustic Soda (NaOH) with temperature 120°C. For the setup of the CFX were used the following parameters in the table 2.

Table 2. Calculation for the setup of CFX

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Molar Mass &quot;SiO₂&quot;</td>
<td>60,0843 mol/sand grain</td>
</tr>
<tr>
<td>Molar Mass &quot;SiO₂&quot; (1 grain)</td>
<td>3,3E-10 grain/mol</td>
</tr>
<tr>
<td>Volumetric Flow Fluid</td>
<td>1900,00 m³/h</td>
</tr>
<tr>
<td></td>
<td>0,528 m³/s</td>
</tr>
<tr>
<td>Mass Flow Fluid</td>
<td>554,17 kg/s</td>
</tr>
<tr>
<td>Sand mass volume</td>
<td>2000,00 kg/day</td>
</tr>
<tr>
<td>Sand mass flow</td>
<td>0,0231 kg/s</td>
</tr>
<tr>
<td></td>
<td>23.148 g/s</td>
</tr>
<tr>
<td>Sand Density</td>
<td>2650,00 kg/m³</td>
</tr>
<tr>
<td></td>
<td>2.65 g/cm³</td>
</tr>
<tr>
<td>1 Kg</td>
<td>1,00 Kg</td>
</tr>
<tr>
<td>Sand grain mass</td>
<td>1,98E-08 Kg</td>
</tr>
<tr>
<td>Particles</td>
<td>5,04E+07 part/Kg</td>
</tr>
<tr>
<td></td>
<td>1,17E+06 part/s</td>
</tr>
<tr>
<td></td>
<td>1,01E+11 part/day</td>
</tr>
<tr>
<td>Sand mass volume</td>
<td>2000,00 kg/day</td>
</tr>
<tr>
<td>Number of positions</td>
<td>2000,00</td>
</tr>
</tbody>
</table>

To perform the simulation it was used a hydrocyclone sand separator dimension as shown on the figure 1 and figure 2 computational meshes for the test hydrocyclone.
Figure 1. Schematic dimensions of the hydrocyclone sand separator

The perforated insert is the main subject of this study and to get accurate simulation and prediction of erosion the mesh of this part of hydrocyclone sand separator it was refined with medium mesh. Refinement mesh is recommended to capture gradients of concern such as velocity, pressure, temperature, etc. Mesh quality and smoothness critical for accurate results and this leads to larger mesh sizes, often millions of elements.

The holes of the perforated have 12mm of diameter and spaced equally @ 25.4mm. The total amount of holes is around 3950. As mentioned earlier due the amount of hole needed, it was used a computer with Intel processor i7 3.4 GHz with turbo booster to 4 GHz, 16 GB of memory RAM and hard disk with 2 TB.

The total of elements for this simulation is 19.282.844 and 3.638.021 nodes. The figure 2 below shows the mesh of the geometry. The mesh used is composed of tetrahedral elements, containing layers of prismatic cells next to walls (inflated boundaries). These inflated boundaries are important for numerical resolution and more accurate in the region where the higher speed gradients (next to the walls). The mesh was also refined close to the perforated insert of the cyclone, where there may be change in flow direction.

Boundary conditions and fluid properties were chosen to represent the real operating conditions. A mass flow boundary condition was considered at domain inlet and a constant pressure condition at outlets. To solve the simulation, it was created two sets of identical particles. The first set is fully coupled to predict the effect of the particles on the continuous phase flow field and allow the particles to influence the flow field. The second set is one-way coupled with higher number of particles to provide a more accurate calculation of the particle volume fraction and local forces on walls, but without affecting the flow field.
Figure 2. Mesh grid with medium refinement

Table 3. The main parameters for the boundary conditions.
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The table 3 shows the main parameters for the boundary conditions.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>Steady State</td>
</tr>
<tr>
<td>Advection Scheme</td>
<td>High Resolution</td>
</tr>
<tr>
<td>Turbulence Numerics</td>
<td>First Order</td>
</tr>
<tr>
<td>Residual</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>Convergence Criteria</td>
<td>RMS</td>
</tr>
<tr>
<td>Time Scale</td>
<td>Auto Timescale</td>
</tr>
<tr>
<td>Morphology</td>
<td>Continuous Fluid</td>
</tr>
<tr>
<td></td>
<td>Particle Transport Solid</td>
</tr>
<tr>
<td>Temperature</td>
<td>120 °C</td>
</tr>
<tr>
<td>Pressure</td>
<td>700 kpa</td>
</tr>
<tr>
<td>Inlet Mass Flow Rate</td>
<td>554,694 kg/s m⁻¹</td>
</tr>
<tr>
<td>Outlet &quot;Overflow&quot;</td>
<td>700 kpa</td>
</tr>
<tr>
<td>Outlet &quot;Underflow&quot;</td>
<td>Wall</td>
</tr>
<tr>
<td>Perforated Insert</td>
<td>Wall</td>
</tr>
<tr>
<td>Vortex Breaker</td>
<td>Solid Domain</td>
</tr>
<tr>
<td>Sand Volumetric Concentration</td>
<td>0.0042 %</td>
</tr>
<tr>
<td>Erosion Model</td>
<td>Finnie</td>
</tr>
<tr>
<td>Drag Force</td>
<td>Shiller Naumann</td>
</tr>
<tr>
<td>Sand Fully Couple &quot;SFC&quot;</td>
<td>2000 positions</td>
</tr>
<tr>
<td>Particle Mass Flow Rate &quot;SFC&quot;</td>
<td>0.0115 kg/s m⁻¹</td>
</tr>
<tr>
<td>Sand OneWay &quot;SOW&quot;</td>
<td>5000 positions</td>
</tr>
<tr>
<td>Particle Mass Flow Rate &quot;SOW&quot;</td>
<td>0.0115 kg/s m⁻¹</td>
</tr>
<tr>
<td>Coefficiente Restitution &quot;Perforated Insert&quot;</td>
<td>0.75</td>
</tr>
<tr>
<td>Sand Fully Couple &quot;SFC&quot;</td>
<td>0.75</td>
</tr>
<tr>
<td>Sand OneWay &quot;SOW&quot;</td>
<td>0.75</td>
</tr>
</tbody>
</table>

4. RESULTS AND DISCUSSION

The sequence of figures below with different turbulence model shows the erosion map for an industrial hydrocyclone sand separator using particle diameter distribution according to table 1. The results show that the particles follow a distinct path rather than cluttering on the cyclone walls while swirling down. Most severely eroded sites were the top part of the perforated insert and in the middle. It was observed also some erosion in the top and in the conical part of the hydrocyclone. This observation is in accordance with the experimental findings in the mills where we have installed the sand separators. This demonstrates the sensitivity of the erosion mainly in the perforated insert that is the subject of this paper.
Figure 3. SST sand fraction volume
Figure 4. RNG k-ε sand fraction volume

Figure 3. SST perforated insert erosion
Figure 4. RNG k-ε perforated insert erosion

Figure 4. SST perforated insert erosion
Figure 5. RNG k-ε perforated insert erosion
Figure 6. SST perforated insert erosion

Figure 7. RNG k-ε perforated insert erosion

Picture 1. Perforated insert worn out

Picture 2. New Perforated insert
Figure 7. SST Sand Sep. Vessel erosion

Figure 8. RNG k-ε Sand Sep. Vessel erosion

Picture 3. Sand Separator worn out

Picture 4. Sand Separator worn out
Figure 8. SST Sand Sep. Pressure Profile

Figure 9. RNG k-\(\varepsilon\) Sand Sep. Pressure Profile

Figure 9. SST Sand Sep. Velocity Profile

Figure 10. RNG k-\(\varepsilon\) Sand Sep Velocity Profile
5. CONCLUSIONS

The results obtained show that turbulence model SST and RNG k-ε achieved the target of this study and in both simulations the erosion caused by abrasive action of sand are located in the same region of the perforated insert. This modeling was validating with the experimental results that shows the wearing in exactly the same place. Beside the both turbulence models achieve satisfactory results, the SST turbulence seems to be more accurate and recommended for this application. This can be seen on the figures 4 and 5 that show the erosion in the perforated insert similar to the picture 1. Also the figure 11 the velocity profile in the center of the perforated insert is slightly higher if compared to figure 12.

The enormous computational requirements, even for the minimal modeling of hydrocyclone phenomena, have limited our ability to go beyond a simple understanding of the flow structures, collection efficiency and global design issues. More systematic research for addressing the other important issues, such as reasonable estimates of the cyclone natural length and vortex finder dimensions, is needed. With increasing computational power, it is envisaged that in the near future we will be able to perform fully resolved simulations on hydrocyclones which will not only answer the above questions but will also advance our knowledge of hydrocyclone operations and erosion even optimize them for specific operational circumstances.

REFERENCES


