CFD Analysis of the oil-water separation performance on hydrocyclones with functionalized surfaces

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The present work seeks to simulate the three dimensional oil-water turbulent flow and oil separation process on a traditional deoiling hydrocyclone using STAR-CCM+ CFD (Computational Fluid Dynamics) software. In order to evaluate the effect of the implementation of functionalized surfaces on the deoiling process, The Reynolds Stress model and the eulerian-eulerian model are combined to handle the complex anisotropic turbulent two-phase flow. Velocity and pressure profiles were obtained for a single phase simulation in order to evaluate the flow behavior on the hydrocyclone. Then, oil volume fraction, velocity, and pressure profiles were obtained for a multiphase simulation and the results were in agreement with previously reported data in the literature. At last, surface functionalization was implemented on the monophasic simulation due to convergence issues with the multiphase modified simulation. The results were not conclusive towards the effect of surface functionalization on separation performance but strongly showed the need of continuing this work into the multiphase simulation or experimental research.

Keywords: Deoiling hydrocyclone, CFD, Anisotropic turbulent, eulerian-eulerian model, Reynolds Stress model.

1. Introduction

Water tends to become the dominant produced fluid in oil production. Globally, it is estimated that 3 barrels of water are extracted for each oil barrel (Universidad Estatal de Nuevo Mexico, Centro de investigacion agricola Farmington, 2012), value that varies with mature wells. On Rubiales Oil Field, 9 barrels of water are produced for each oil barrel which demonstrates how high can this proportion get (RWL Water group). At the same time, Produced Water (PW) should meet the international standards in terms of oil-residuals fraction (Young & Wakley, 1993), besides this stringent standards and the magnitude of PW, progressing into deeper water and more hostile environments in the search for new oil and gas reserves has also placed and increasing demand on the industry to develop lighter, more compact, and more efficient process equipment to replace their traditional counterparts (Meldrum, 1987). One solution to the mentioned problem is the use of hydrocyclone separators, in contrast to conventional produced water treatment systems; hydrocyclones provide offshore and onshore operators the benefits of light weight, compact size, easy and reliable operation, low maintenance, complete insensitivity platform motions, low utility requirements, and highly predictable capacity (Choi, 1990).

The modern renaissance in deoiling hydrocyclone was instigated by martin Thew and Derek Colman at the University of Southampton (Woodruff, 1990); Hydrocyclones technology has been designed to generate high centrifugal forces (over one thousand times the force of gravity) without creating significant droplet shear (Schubert, 1992).

As shown in figure 1, water-oil mixture is fed tangentially under pressure through the inlet chamber forcing rotation of the fluids within the device. As the fluid is forced down the liner, the two conical shape sections (Reducing section and Tapered Section) of the hydrocyclone, accelerates the fluid into a helical pattern setting up a vortex and creating large centrifugal forces, this forces cause the lighter material (oil) to migrate to the hydrocyclone axis, while the denser material (water) is forced to the outer wall (Bowers, 1998), under this conical shape sections there’s another cylindrical section (Tail-Pipe-section) with the purpose of maintaining the swirl effect as long as possible. By maintaining the underflow outlet at a higher pressure than the overflow outlet, the concentrated oil core of the vortex is forced to flow
counter-current to the main flow (Bowers, 1998), resulting on a concentrated oil stream on the overflow and a free oiled water on the underflow.

The deoiling hydrocyclone performance depends on many parameters that are usually grouped in three categories; dimensions, feed characteristics and flow characteristics (Kharoua et al, 2009). There have been many experimental studies on hydrocyclones; some of them are summarized in Table 1. Due to the complex multiphase swirling flow on hydrocyclones, only few studies have worked with numerical simulations using CFD, some of them can be seen on Table 2.

2. Present Work

The aim of this work is to evaluate the effect of the implementation of functionalized surfaces, which are capable of modifying the slip condition, on the oil/water separation performance of a typical deoiling hydrocyclone.

<table>
<thead>
<tr>
<th>Table 1. State of art on experimental studies.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Synopsis</strong></td>
</tr>
<tr>
<td>Performed the first measurements on velocity profiles on hydrocyclones</td>
</tr>
</tbody>
</table>
| Performed experiments to study deoiling hydrocyclones and concluded that separation efficiency is independent of the flow split if it is between 0.5 and 10 %, they also concluded that for a constant droplet size distribution at inlet, the size distribution in the outlet is independent of the flow split. | • Colman & Thew, 1980  
• Colman, 1981  
• Colman & Thew, 1983 |
| Studied the problems of using hydrocyclones for water treatment | Thew, 1986 |
| Presented the operational curves, principle and the first field study of hydrocyclones. | Meldrum, 1987 |
| Determined tangential and axial velocities for modeling purposes using Laser Doppler Velocimetry (LDV). | Hsieh, 1991 |
| Studied the effect of operational parameters and investigated ideal hydrocyclone dimensions in terms of cylindrical diameter, cone angle, and tail-pipe section length and did the first attempt on optimizing a 35-mm hydrocyclone. | Young & Wakley, 1993 |
| Studied the velocity field on a hydrocyclone. | Zhi-Shan et al, 2009 |
| Studied the distribution of oil droplets in deoiling hydrocyclones. | Zhou & Gao, 2009 |
| Determined the effects of the flow-split ratio and the flow rate on the oil/water separation performance. | Hai-fei et al, 2012 |

Hydrophobic surfaces are going to be use for this functionalization due to their capacity for modifying the slip condition. In particular, changes in fluid-surface interactions, such as wetting ability of the fluid, may affect the ability of the fluid to exchange momentum with the surface at the atomic scale, resulting in a velocity slip at the solid wall (Choi et al, 2002). Slip length is the parameter that quantifies this “slip”. The slip length is defined as the distance into the wall by which the bulk velocity profile must be extrapolated in order to reach a velocity of zero (Fang, 2006); In other words, the slip length is a fictitious distance beneath the solid surface at which a no-slip boundary condition could be applied. The slip length also depends on the interfacial parameters such that the amount of slip increases
with decreasing surface energy corrugation which is achieved by either decreasing the wall-fluid coupling or increasing the wall density (Choi et al, 2002).

Table 2. State of art on CFD studies.

<table>
<thead>
<tr>
<th>Synopsis</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>First successful work in predicting the fluid flow in hydrocyclones.</td>
<td>Rodes, Pericleous, &amp; Drake, 1987</td>
</tr>
<tr>
<td>Exposed the advantages and limitations of different CFD techniques applicable to hydrocyclones modeling and proposed an automated CFD tool for HC design.</td>
<td>Slack et al, 2004</td>
</tr>
<tr>
<td>Simulation for high concentration on dispersed phase and determined separation efficiency based on flow field and phase concentration distribution Turb: RSM MM:Eulerian-Eulerian</td>
<td>Huang, 2005</td>
</tr>
<tr>
<td>Evaluated different inlets designs and obtained higher efficiencies than standard design.</td>
<td>Sooran et al, 2009</td>
</tr>
<tr>
<td>Showed that RSM gives a better solution for deoiling hydrocyclone and studied the effect of inlet concentration, oil droplet diameter and flow rate. Turb: k-ε and RSM MM:Eulerian-Eulerian</td>
<td>Kharoua et al, 2009</td>
</tr>
<tr>
<td>Compared the oil/water separation performance between a cylindrical and square hydrocyclone concluding that cylindrical hydrocyclone has a better performance. Turb: Large Eddy Simulation (LES) MM:Eulerian-Eulerian</td>
<td>Rosales et al</td>
</tr>
</tbody>
</table>

As a whole, it appears that wetting liquids satisfies no slip conditions on the boundaries. On the other hand, there has been a substantial amount of analytical, numerical, and experimental works that includes a increasing on slip length with the use of hydrophobic surfaces which makes the no-slip boundary condition innapropiate for these type of surfaces. Churaev & Sobolev (1984) Investigated the slip effects of mercury in thin quartz capillaries smaller than 1 µm in radius, and found that the slip length was approximately of 30nm for water flow. Ruckenstrein & Rajora (1983) also measured the slip velocity in flow through capillaries with solid surfaces made repellent to the liquid and suggested that slip does not occur directly over the solid surface but over a gap, which is generated when the liquid and the solid have different natures. Walther et al, (2002) Studied the no-slip boundary conditions for water at a hydrophobic surface using non-equilibrium molecular dynamics simulations and reported a slip length of about 64 nm, besides this, they reported a value of 14 nm by changing the properties of the interface from hydrophobic to hydrophilic. Tretheway & Meinhart (2002) used micron-resolution particle image velocimetry to measure the velocity profiles of water flowing though hydrophilic and hydrophobic channels. Their result suggested an acceptance for no slip boundary condition for the hydrophilic channel and a presence of slip on the hydrophobic channel, more precisely, a slip length of approximately 1 µm, over 100 times greater than other researchers.

Many other authors have reported much higher values of slip lengths by using super-hydrophobic surfaces which consists of microgrooves, pillars or posts patterned on the solid surface which are coated with a thin hydrophilic layer. Ou et al, (2004) investigated the flow through microchannels with one of the channel walls containing a superhydrophobic surface, Pressure drop reduction up to 40% and apparent slip lengths larger than 20 µm were reported with groove and posts geometries. Choi et al, (2006) nanofabricated gratings on a flat surface to obtain a nanograted superhydrophobic surfaces, they obtained slip lengths of 100-200 nm and indicated that these type of surfaces enable directional control of the slip. Choi & Kim, (2006) Measured slip lengths of 20 µm for water in a cone-plate rheometer with the stationary plate patterned with nanoposts of...
hydrophobic material. Lee et al. (2008) reported a slip length as large as 185 µm achieved using surfaces patterned with posts or gratings.

Taking into account these studies, in order to implement the functionalization of the surface, the no-slip boundary condition will be changed for a slip model with values of slip lengths corresponding to hydrophobic surfaces.

In this work, a monophasic simulation using water was done in order to initially evaluate the flow behavior in the hydrocyclone, then, the multiphase simulation was implemented and compared with experimental results, and finally, the simulation was done with the functionalized surface and results were compared on a monophasic phase with a setup with no functionalization on the surface (no-slip).

3. Modeling setup

For the modeling of the anisotropic turbulent multiphase of the deoiling hydrocyclone on STAR-CCM+, the eulerian-eulerian approach combined with the Reynolds stress turbulence model was used.

3.1 Eulerian-Eulerian Approach for multiphase flow

There are two approaches for the numerical calculation of multiphase flows: the euler-lagrange approach, and the Euler-Euler approach. In Euler-Lagrange approach, the prime-phase fluid is treated as a continuum by solving the Navier-Stokes equation, while the dispersed-phase fluid is solved by tracking a large number of individual droplets. The euler-euler approach is usually more complex, in this approach, the different phases are treated as interpenetrating continua (Huang, 2005). The model shares a single pressure field for both phases and solves the momentum and continuity equations for each phase and couples the results through an interphase exchange coefficients. The algebraic slip mixture approach for dispersed phase flow was chosen because it allowed consideration of the problem at low computational cost in relation to traditional eulerian-eulerian approach.

Interactions between droplets were neglected so shear and coalescence effects were not taken into account.

3.2 Turbulence model: Reynolds Stress Model

The Reynolds Stress Model (RSM) is the most elaborate turbulence model. Abandoning the isotropic eddy-viscosity hypothesis, the RSM closes the Reynolds-averaged Navier-Stokes equations by solving transport equations for the Reynolds stresses, together with an equation for the dissipation (Zhi-shan Bai, 2006). The RSM accounts for the effects of streamline curvature, swirl, and quick changes in stress rate in a more rigorous manner (Sooran, Seyed, & Hashemabadi, 2009). Based in the current state of art on CFD studies, and on the anisotropic approach of RSM, and on the state of art on CFD studies, the RSM model was selected from the STAR-CCM+ model library. On the other hand, the pressure strain correlation chosen was the linear pressure strain.

Due to the computational cost of implementing Reynolds stress model, the “turbulence response” tool offered by STAR-CCM+ software was implemented. This tool permits solving eulerian-eulerian approach by solving RSM model for the continuum phase only, and this solution is transferred with a factor to the dispersed phase, so the dispersed phase receives all the turbulent information from the continuum phase which reduces the computational cost of solving the model but increases the error on the simulation results. At last, the tool was not implemented due to its huge error respect experimental data.
3.3 Surface Functionalization

In order to implement the surface functionalization the no-slip boundary condition will be abandoned and a slip model will be used, this model is described on the following expression:

\[
v_{z=0} = b \frac{\partial v}{\partial z}
\]  

(1)

In Equation 1, \(v_{z=0}\) is the velocity at the wall, \(b\) is the slip length, and \(z\) is the normal at the wall inwards to the liquid.

The no-slip boundary condition was chosen on STAR-CCM+ software with an option for fixing the velocity at the wall instead of using the conventional configuration which fixes a zero velocity at the wall, this velocity was calculated with an user function that takes into account the slip model previously shown. For the implementation of the model, a value of 1 µm of slip length was used which was a value obtained by Tretheway & Meinhart, (2002) and a value of 5 µm that was chosen in order to verify the independence of the solution with slip length. It is important that lower and upper values of slip lengths are proven on a future work due to the wide gap of slip lengths values that are reported on literature; the upper values of slip length can be proven by using high values of slip length or by changing the geometric slip configuration in order to represent the patterns present on these super-hydrophobic surfaces.

As it is seen on the slip model, the velocity is calculated for one direction, so these model will be extrapolated for three dimensions by using the same value of slip length as an approximation for this work.

These functionalization was programmed by using the following user-defined function:

\[
u_{\text{wall}} = u - b \frac{\partial u}{\partial n}
\]  

(2)

Were \(u\) is the instant velocity at the wall, \(b\) is the slip length and \(u_{\text{wall}}\) is the slip velocity that will be calculated by this function. Besides the user function, a table is created, this table is filled with the result of the user function in every cell that touches the wall; and the information of these table is used as the velocity vector fixed on the slip boundary condition.

Two simple pipe flow simulations were done to represent how this boundary condition works, one of them with a conventional no-slip boundary conditions and the other with a 1 µm slip. A velocity inlet and pressure outlet boundary conditions were chosen with a velocity of 0.5m/s at inlet. Velocity profiles of the same cross sectional area were obtained as it is seen on Figures 9-10 on Annex 1, these figures shows the expected results because the slip simulations shows higher velocity values on its profiles, this is seen on the maximum value on the color bar which represent the maximum velocity value present on the profile. This is an expected result due to the non-zero velocity of a slip boundary condition which is seen on the profiles. This situation can also be visualized on Graph 1.

As it is seen, the slip boundary condition had an expected effect on the simulation, therefore it could be implemented on the hydrocyclone, however, due to convergence problems present on the multiphase simulation, the analysis was done on the single phase simulation for the reasons that will be explained on the next section. Although, multiphase simulation results will still be shown as an advancement for a future work.

3.4 Single Phase Analysis for the effect of surface functionalization.

The main reason for the convergence problems mentioned is that the table that contains the
information for the slip velocity in each cell must be constantly updated with a new calculation of slip velocity that uses the velocity on the wall of the actual iteration, these updates are necessary in order to maintain a proper value for the boundary condition.

The update frequency of these boundary condition is a key parameter for the convergence of the simulation, low frequencies are needed at the beginning of the simulation followed by higher frequencies, if necessary, until the boundary condition and solution converges together. Due to the need of unsteady simulations for the multiphase flow, convergence by managing these updates becomes challenging since you have to update your boundary condition in iterations and time steps which forces the user to constantly modify the number of iterations per time step and the update frequency in order to maintain a proper and stable solution. With the advance of iterations and time.

Due to this situation, it was decided to try running the simulation in different trials using combinations of iterations per time step and update frequencies. On these trials, low and high numbers of inner iterations were tried with high and low frequencies in around 6 different trials. Low frequencies with high number of inner iterations did not diverge but its simulation time was enormously large. None of the other trials converged, so it was not possible to do a correct comparison using the multiphase simulation.

Due to the lack of convergence on the modified multiphase simulation, it was decided to implement the surface functionalization on the single phase simulation in order to find important differences that could theoretically influence the separation performance.

4. Problem Identification
4.1 Geometry
In this study a standard hydrocyclone design was used, the geometry details of the design can be seen on Figure 11 on annex 1. Which is the same design used in (Sooran et al, 2009). This is a vertical hydrocyclone but is on a horizontal perspective so gravity acts from left to right, the geometric diagram of the hydrocyclone can be seen on Annex 1.

4.2 Boundary Conditions
Three types of boundaries were used for the simulations

Inlet: A velocity-inlet boundary condition was used for a flow rate of $20 \frac{L}{min}$ (Sooran, Seyed, & Hashemabadi, 2009).

Outlet: 2 pressure-outlet boundary conditions were used with 0Pa and 37 kPa on the overflow and underflow respectively (Sooran, Seyed, & Hashemabadi, 2009).

Wall: No slip condition is assumed on walls for the conventional simulation; Implementation of the slip model was done for the modified simulation (slip length

The properties of both phases (oil and water) are summarized on Table 3.

Table 3. Fluid Properties used in the simulation.

<table>
<thead>
<tr>
<th>Component</th>
<th>Density ($\frac{kg}{m^3}$)</th>
<th>Dynamic Viscosity ($\frac{kg}{m*s}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>850</td>
<td>0.00332</td>
</tr>
<tr>
<td>Water</td>
<td>998</td>
<td>0.001</td>
</tr>
</tbody>
</table>
4.3 Mesh Generation

For a marginal error reduction and for a mesh independency test, 6 different meshes were generated and studied for the single phase simulation using water with the following procedure:

First, two tetrahedral meshes were generated, one with a base size of 0.004m (303448 cells) and another one with 0.002m (462500 cells). Their residuals were compared and their pressure profiles were obtained and compared noting that they had similar results but the finer mesh had much higher residuals.

After this method, 2 polyhedral meshes were generated with the following base sizes: 0.002 m (123400 cells), 0.001 m (240700 cells). As it was done for tetrahedral meshes, their residuals and pressure profiles were compared noting that tetrahedral meshes had a better result.

At last, taking into account that the best result was on 0.004 m base size-tetrahedral mesh a modification was done on this trial. A cylindrical shape volumetric control mesh was generated on the axis of the hydrocyclone were the profile showed the low-pressure core (vortex). This was done in order to refine the mesh in this area due to the big gradients present in the vortex, this refinement can be appreciate in Figure 12, Annex 1 which is a cross sectional area of the hydrocyclone. This last generated mesh resulted on a similar result so it was concluded that the final mesh will be the conventional 0.004m base size tetrahedral mesh.

The final mesh can be seen on Figure 2, and residual plot can be seen on Figure 13 in annex 1. Experimental results were not used for the mesh analysis because there was not experimental data for the single phase hydrocyclone.

5. Monophasic simulations results, analysis, and comparisons.

Taking into account that the purpose of this work is to analyze the effect of the surface modification of a deoiling hydrocyclone: at first, a monophasic simulation (using water) was done to be sure that the hydrodynamics on the hydrocyclone were as they should; At last, due to the convergence problems presented on the modified multiphase simulation, the surface functionalization was done on the monophasic simulation, so pressure, tangential velocity, and axial velocity distributions were obtained for the functionalized and for the conventional single phase hydrocyclone in order to analyze the flow behavior to be sure that the hydrodynamics on the hydrocyclone were as they should and to find important differences that could theoretically influence the separation performance.

5.1 Convergence of the modified simulation.

As it was expected, convergence on the single phase simulation was much easier, although it was necessary to run the unmodified simulation and when the solution stabilized the new boundary condition was implemented with an update frequency of 1 update every 100 iterations until the new boundary condition converged within the solution. Residuals diagrams of both modified simulations can be seen on Annex 2 Figures 14-15.

5.2 Pressure Distribution

The distributions of pressure can be seen on Figure 4 and on Annex 2. At first, we can see that there was no significant difference on the pressure profiles presented in Figures 16-17 so focus will be only on the unmodified simulation; there are considerable pressure differences in radial and axial directions, so the oil-water separation principle of operation can be explained from here. The pressure difference
radial direction causes the oil (lighter phase) to migrate to the central core of the cyclone while the centrifugal forces pushes the heavier phase (water) to the walls. After these phenomena, oil migrates from underflow to overflow direction due to pressure difference between underflow and overflow, on the other hand, water flows down the liner due to gravity and pressure difference between top outer shell and bottom outer shell of the cyclone.

The low pressure central core is widely understood and represents the air-core (vortex) generated due to the strong swirling flow.

5.3 Tangential Velocity

Tangential velocity is of great importance on hydrocyclones because this is the one that generates the needed centrifugal force. The tangential velocity distributions can be seen on Annex 2. Focusing on the unmodified tangential velocity cross sectional area profile (Figure 18), the no-slip condition can be appreciate, and it can be seen that tangential velocity increases from the HC outer wall to the air core were it finds a maximum value. This result agrees with experimental observation (Colman & Thew, 1980). On the longitudinal section area profile (Figure 5), the no-slip condition can again be appreciate and the shape of the air-core is visualized. The location of the cross sectional area can be appreciated on this figure.

For the comparison between the modified surface simulation and the no-slip conventional simulation tangential velocities profiles, only the cross sectional area profiles were analyzed because there was no significant differences on the longitudinal profiles. Figures 18-20 shows the tangential velocity profiles on the same cross section area for each of the simulations, increasing values of tangential velocities near the hydrocyclone wall can be noticed by increasing slip lengths, so the no-slip simulation has the lowest tangential velocity near the wall. These higher tangential velocities on water, could favor the fact that water tends to the outer shell what would favor the separation performance due to the hydrocyclon operation principle; Consequently, it is necessary to work either on the multiphase simulation convergence or on an experimental research, in order to visualize the direct effect on separation.
5.4 Axial Velocity
The axial velocity distributions can be seen on Annex 2, the values are negative on the underflow direction. Focusing on the axial velocity distribution for the unmodified simulation (Figure 6), It is seen how the axial velocity is negative near the hydrocyclone wall, which represents the heavier phase that should be flowing downwards; and we can see that it’s positive near the center which represents the lighter phase flowing upwards, this phenomena can be better appreciate on Figure 23 because it shows only positive values. Besides this, a maximum negative value is found at the beginning of the tail pipe section and a maximum positive at the beginning of the vortex finder which is a common behavior on hydrocyclones. Another common behavior it’s seen on the cylindrical section where we have low negative values of axial velocities due to the high tangential velocity component.

On the other hand, comparing the 3 distributions (Figure 6, 21, 22), it can be seen that there’s no significant difference between the 3 results, however, it is necessary to work on the multiphase simulation convergence in order to visualize if there’s an effect because axial movement on the cyclone is strongly affected by density difference.

5.5 Streamlines
Streamlines on the simulated hydrocyclone are seen on Figure 3, the streamlines shows the swirling flow and the high velocities on the inlet chamber which is characteristic on hydrocyclones.

6. Multiphase simulation results and analysis.
Taking into account that the purpose of this work is to analyze the effect of the surface modification of a deoiling hydrocyclone, a multiphase simulation with an unmodified hydrocyclone was done in order to evaluate separation performance, flow behavior, and to compare with experimental results to validate the model for the implementation of the surface functionalization, however, due to the convergence problems previously mentioned, this simulation was done to validate the model, and as an advance for a future work in which convergence is achieved for the multiphase flow.

6.1 Oil Distribution
Figure 7 shows the oil volume fraction profile on the same longitudinal section that has been used for the monophasic analysis, it can be seen that there is an oil concentrated shell near the vortex of the cyclone, and it gets more concentrated on the overflow direction until it reaches the vortex finder.
were it increases to a value around 10%, this is an appropriate result, because, as it was explained before, this is the outlet from which the concentrated oiled-water is extracted. Besides this, the fact that this concentrated oil shell coincides with the zone of oil positive axial velocities as we can see on Figure 8, is favorable for the separation performance.

It is important to mention that both, oil concentrated shell and positive axial velocities disappear below the mid half of the tapered-section what suggests that the tail-pipe-section is over dimensioned.

Figure 4 Pressure profile for no-slip single phase hydrocyclone simulation.

Figure 5 Tangential velocity profile for no-slip single phase hydrocyclone simulation on a longitudinal section, with position of the cross sectional area.

Figure 6. Axial velocity profile for no-slip single phase hydrocyclone simulation.

Figure 7. Oil volume fraction distribution for the multiphase no-slip hydrocyclone simulation.
6.2 Model Validation

It was necessary to validate the model before their application for the analysis of flow through the modified hydrocyclone. The criterion used to evaluate hydrocyclone performance is separation efficiency defined as:

\[ E = \frac{\alpha_o Q_o}{\alpha_{in} Q_{in}} \]  \hspace{1cm} (3)

Where \( \alpha \) stands for oil volume fraction, \( Q \) for volumetric flow, and the subscripts “o” and “in” refers to overflow and inlet respectively. This separation efficiency represents the fraction of the oil that has been extracted from the inlet.

Oil droplet size in the feed is one of the important parameters that change the performance of a deoiling hydrocyclone (Soran et al, 2009). Simulations were carried out for different oil droplet sizes (25, 50, and 70 µm) and their separation efficiencies were calculated and compare with experimental results used by Sooran et al, (2009) reported by Belaidi & Thew, (2003). Table 4 summarizes this comparisons.

Table 4 Comparison of reported data and numerical results for different mean droplet sizes at inlet.

<table>
<thead>
<tr>
<th>Oil droplet size (µm)</th>
<th>Calculated Efficiency (%)</th>
<th>Reported Efficiency (%)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>43.8</td>
<td>50</td>
<td>12.3</td>
</tr>
<tr>
<td>50</td>
<td>49.9</td>
<td>80</td>
<td>37.6</td>
</tr>
<tr>
<td>70</td>
<td>56.8</td>
<td>85</td>
<td>33.1</td>
</tr>
</tbody>
</table>

The simulation with an oil droplet inlet size of 25µm present the best result with only 12.3% of error away from the reported data, so this will be the simulation in which the surface functionalization should be tested once the convergence issue is solved.

7. Conclusions

The effect of implementing functionalized surfaces that are capable of changing the slip conditions, as hydrophobic surfaces do, was correctly evaluated for a single phase standard hydrocyclone simulation using water. Results for the multiphase flow were not obtained due to convergence issues on the functionalized multiphase hydrocyclone, however, the unmodified model was simulated and results are in agreement with reported data, which permits the model to be correctly analyzed once the convergence issue is solved.

Based on the obtained results, the following points can be made:

- The flow behavior described on the pressure, axial velocity, and tangential velocity profiles is in agreement with the desired and conventional behavior of deoiling hydrocyclones.
- Oil volume fraction profile showed a desired and correct behavior of oil inside the hydrocyclone.
- There was not significant effect of the surface functionalization on Pressure and axial velocity profiles, however, tangential
velocity profile showed that functionalized surfaces result on a higher tangential velocity of water near the wall which could improve the hydrocyclon separation performance.

- The results for the effect of the surface functionalization on oil separation were not conclusive for a multiphase flow but the results of the functionalized single phase hydrocyclone strongly recommends to proceed with an experimental research or to work on the convergence issues of the multiphase simulation.

8. Future work

Based on the results obtained and on the detected limitations, it is suggested to further work on the following issues:

- Solve the convergence problems in order to evaluate the effect on the oil/water separation of the deoiling hydrocyclone.
- Investigate how the slip model can be extrapolated to 3 dimensions without assuming the same slip length in each direction.
- Higher values of slip length should be tested for two reasons:
  - Make sure that the lack of effect is because there’s no effect and not because there’s not enough slip.
  - To represent the patterned super-hydrophobic surfaces described before.
- Include coalescence and shear effect taking into account that this was an important source of error.

- Try with different configurations of functionalization, these includes:
  - Functionalize different combinations of sections of the hydrocyclone (inlet chamber, reducing, tapered, tail-pipe) taking into account the purpose of each one of these.
  - Implementing geometric patterns were the function is functionalized to represent the super-hydrophobic surface.

9. Bibliography

○/pw/


condition for water at a hydrophobic, dense surface.


Annex 1

Figure 9. Cross sectional tangential velocity profile for no-slip pipe-flow simulation.

Figure 10. Cross sectional tangential velocity profile for 1µm slip length pipe-flow simulation.
Figure 11. Geometry Details of the hydrocyclone design.

Figure 12. Close up mesh on cross section of the finer mesh in vortex.

Figure 13. Residual Diagram for single phase hydrocyclone simulation with a 0.004m base size tetrahedral mesh.
Annex 2

Figure 14. Residual Diagram for 1 µm slip length single phase hydrocyclone simulation.

Figure 3 Residual Diagram for 5 µm slip length single phase hydrocyclone simulation.

Figure 4 Pressure profile for 1 µm slip length single phase hydrocyclone simulation.

Figure 5 Pressure profile for 5 µm slip length single phase hydrocyclone simulation.
Figure 6 Cross sectional Tangential velocity profile no-slip length single phase hydrocyclone simulation.

Figure 7 Cross sectional Tangential velocity profile for 1 µm slip length single phase hydrocyclone simulation.
Figure 20. Cross sectional Tangential velocity profile for 5 µm slip length single phase hydrocyclone simulation.

Figure 21. Axial velocity profile for 1 µm slip length single phase hydrocyclone simulation.

Figure 8 Axial velocity profile for 5 µm slip length single phase hydrocyclone simulation.
Figure 9 positive values of axial velocity profile for no-slip single phase hydrocyclone simulation.