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NUMERICAL MODELLING OF AIR CORE IN HYDROCYCLONES

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ABSTRACT

Numerical simulations of the flow through a 75mm diameter hydrocyclone were used to investigate the different approaches for the air core diameter predictions. Single phase and multiphase approaches were explored. The saturation pressure of water was used to predict the air core for the single phase simulations. Two turbulence models, Reynolds Stress Model (RSM), and Large Eddy Simulation (LES), were compared, both of which yielded good agreement within an average difference of 8.8% and 6%, respectively. The influence of the multiphase approach on the numerical predictions was also investigated by comparing the Volume of Fluid (VOF) and the mixture model. The VOF model was found to fit the experimental data slightly better than the mixture model within an average difference of 2.9%. Overall, the results showed that the choice of multiphase approach and the turbulence model in the CFD modelling of the air core can improve the numerical predictions.

NOMENCLATURE

g_i gravitational acceleration vector
p pressure
t time
u_i velocity vector
$\vec{v}_a$ velocity vector of air
$\vec{v}_{am}$ drift velocity vector
$\vec{v}_{aw}$ velocity vector of air relative to water
$\vec{v}_m$ mixture velocity vector
$\vec{v}_w$ velocity vector of water
x_i displacement vector
y+ dimensionless distance from the wall to the first grid point
a_a air volume fraction
ρ density
τ_{ij}^{sgs} Reynolds stress tensor
μ fluid viscosity

INTRODUCTION

Hydrocyclones are used in most mineral processing industries as a centrifugal-type separator for classification, desliming and thickening. Pressurized slurry is fed into the hydrocyclone through a tangential inlet forming two spiral flows. The outer vortex is a downward stream carrying the coarse particles to the underflow, while the inner spiral flow captures the fine particles and transfers them to the overflow pipe. Since the hydrocyclone operates with two outlets opened to the atmosphere, a central cylinder of air will be developed inside the hydrocyclone. The importance of the air core in the hydrocyclone operation is that its shape and geometry indicate the hydrocyclone performance (Neesse and Dueck, 2007). Further, the diameter of the air core affects the flow splits and the separation efficiency.

Early air core modelling techniques relied on the empirical correlations of geometrical and operational parameters with the air core diameter. For instance, Davidson (Davidson, 1995) introduced a correlation to predict the air core radius based on the flow features at the outlets. In another work Concha et al. (Concha et al. 1996) correlated the air core diameter with the pressure drop, the liquid viscosity and the ratio of underflow/overflow diameters. However, these early empirical equations were hampered by using extensive experimental data and the assumption of a constant air core size along the hydrocyclone.

Computational Fluid Dynamics, (CFD), offers an alternative to model the hydrocyclone based on the physical insights into the underlying hydrodynamics of the flow inside the device. One of the earliest numerical modelling studies of the hydrocyclone was performed by Davidson (Davidson, 1988) who studied the steady state flow of water through a hydrocyclone operating without an air core. The predicted velocity components were compared with experimental data reported by Knowles (Knowles et al., 1973) and showed good agreement. In the same year Hsieh and Rajamani (Hsieh, 1988, Hsieh and Rajamani, 1988) developed their two-dimensional CFD model for a 75mm hydrocyclone. They validated the numerical results with laser Doppler anemometry measurements of the velocity components. They also suggested that the air core can be assumed to be a cylinder with a constant diameter for the whole length of the hydrocyclone. Subsequent studies focused on the three dimensional modelling of the hydrocyclone. Solving the Navier-Stokes equations, Dyakowski et al. (Dyakowski et al., 1999) investigated the laminar flow behaviour inside the hydrocyclone without the air core. In the follow up study, Nowakowski et al. (Nowakowski et al., 2004) suggested that for a successive numerical modelling of the hydrocyclone the interface between the air and water should be captured with the proposed method of Osher and Sethian (Osher and Sethian, 1988). In 2006 Brennan (Brennan, 2006) performed 3D multiphase simulations of the 75mm hydrocyclone of Hsieh to investigate the different approaches for the air core modelling. He compared the VOF and mixture multiphase models in conjunction with two different turbulence models, RSM and LES. Consequently, he recommended a step-wise strategy to resolve the air core inside the hydrocyclone and emphasized on the need for performing simulations for various feed flow rates or other hydrocyclone geometries.

One year later, Neesse and Dueck (Neesse and Dueck, 2007) formulated a semi-empirical equation based on the force balance at the gas-liquid interface. They showed that it is impossible to suppress the air core within the hydrocyclone due to the existence of the dissolved or the dispersed air in the feed. Toward better understanding of the air core behaviour Doby et al. in 2008, (Doby et al., 2008) solved the laminar flow within a hydrocyclone to study the effect of viscosity on the air core formation using pressure distribution inside the hydrocyclone. Their numerical results indicated a greater air core size for the low viscosity feeds. Gupta et al. (Gupta et al., 2008) conducted CFD simulations and experiments to study the effect of air core size on the pressure drop along the hydrocyclone. They eliminated the gas core by inserting a solid rod into the hydrocyclone and analysed the pressure drop in the absence and presence of the air core. It was found that by increasing the flow rate, the air core diameter becomes thicker and it caused more turbulence in the hydrocyclone. Delgadillo and Rajamani (Delgadillo and Rajamani, 2009) conducted LES/VOF simulations of the hydrocyclone to investigate the influence of the geometrical parameters as well as the fluid viscosity on the air core diameter. The relationship between the air core size and the fluid viscosity was found to be similar to the work of Doby et al. (i.e., a decrease in the air core diameter by increasing the viscosity of the fluid). They also suggested that the LES turbulence model is not an economical choice for the hydrocyclone modelling and it requires an extreme mesh resolution to capture all the turbulent fluctuations. More recently, Narasimha et al. (Narasimha et al., 2012) developed a mathematical model to predict the air core under different operating conditions of the hydrocyclone. The benefit of this semi-empirical model is that it embodies the impact of solid particles on the air core diameter.

Considering the work of Doby et al. (Doby et al., 2008) and Brennan's suggestion (i.e., exploring the effects of various feed flow rates on the air core size) the aim of this paper is to investigate different approaches for the air core modelling. The concept of saturation pressure (i.e., the pressure at which the phase change occurs) is employed to predict the air core diameter in the turbulent flow of water. Different turbulence models were tested for single-phase simulations.

Two different multiphase models, i.e. the VOF and the mixture models are compared for the air core modelling. This is followed by the multiphase modelling of the air core for four different feed flow rates to provide additional insight into the air core diameter-feed flow rate trend. In addition, the single-phase and the multiphase modelling methods are validated with the experimental measurements of Hsieh (Hsieh, 1988). It must be noted that the main differences between this work with that of Brennan (Brennan, 2006) are the use of the saturation pressure concept to predict the air core diameter for the single-phase modelling and the parametric study of the effect of various feed flow rates on the air core diameter.

METHODOLOGY

The Reynolds average continuity and momentum equations were solved to model the swirling flow within a 75mm diameter hydrocyclone based on the geometry of Hsieh (Hsieh, 1988).

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial (u_i)}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial(\rho(u_i))}{\partial t} + \frac{\partial\left(\rho(u_i)(u_j)\right)}{\partial x_j} = -\frac{\partial(p)}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial(u_i)}{\partial x_j}\right) - \frac{\partial}{\partial x_j}\left(\tau_{ij}^{sgs}\right) + \rho g_i \qquad (2)$$

In the these equations, u_i is the velocity vector, x_i is the displacement vector, ρ is the fluid density, t is the time, P is the pressure, μ is the fluid viscosity, g_i is the gravitational acceleration vector, and τ_{ij}^{sgs} is the Reynolds stress tensor.

The Reynolds stresses in Eq. (2) were computed by two turbulence models, RSM and LES, since it has been shown that turbulence models established on Boussinesq hypothesis are unable to correctly predict the highly turbulent flow inside the hydrocyclone(Karimi et al., 2011, Delgadillo and Rajamani, 2005). The details of equations for the turbulence models are provided in these articles (Karimi et al., 2011, Karimi et al., 2012).

In the current study, the Volume of Fluid (VOF) model and the mixture model are applied to capture the interface between the air and water. A single set of momentum equation is solved for the fluid mixture, and an additional transport equation to track the volume fraction of air:

$$\frac{\partial \alpha_a}{\partial t} + \nabla \cdot (\alpha_a \vec{v}_m) + \nabla \cdot (\alpha_a \vec{v}_{am}) = 0 \qquad (3)$$

where α_a is the volume fraction of the air phase, $\vec{v}_m$ is the mixture velocity vector, and $\vec{v}_{am}$ is the drift velocity vector. The drift velocity can be computed as:

$$\vec{v}_{am} = \vec{v}_{aw} - \sum_{k=1}^{n} \frac{\alpha_k \rho_k}{\rho_m} \vec{v}_{ak} \qquad (4)$$

$$\vec{v}_{aw} = \vec{v}_a - \vec{v}_w \qquad (5)$$

where $\vec{v}_{aw}$ is the velocity vector of air relative to the velocity of water, $\vec{v}_a$ is the velocity vector of air, and $\vec{v}_w$ is the velocity vector of water.

The differences between mixture and VOF models are in the computation of the air volume fraction and using the concept of relative velocity for the mixture model.

In the mixture model, the value of the air volume fraction lies in the range of 0 to 1, whereas the VOF formulation assumes that the air and water are not interpenetrating (i.e., the cell is either empty or full of air). The second difference between these two multiphase approaches is that the VOF model does not provide equations to calculate the drift velocity.

Of the three multiphase models including Eulerian-Eulerian, mixture, and VOF, this work has applied two, namely VOF and mixture method for the multiphase modelling. The main challenge of using Eulerian-Eulerian multiphase model is the problem of intensive computational time required for solving the continuity and momentum equations for each phase.

NUMERICAL APPROACH

For single-phase modelling the Reynolds average Navier-Stokes (RANS) equations were solved for the unsteady and turbulent flow of water inside a 75mm diameter hydrocyclone. To compute the Reynolds stresses, τ_{ij}^{sgs}, in Eq. (2) two turbulence models were compared. The independency of the solution from the grid size was examined by a grid independence study and an independent solution was obtained for a hexagonal mesh scheme with 226,724 cells. Also, to capture the temporal turbulent fluctuations close to the wall, the maximum y+ (i.e., the dimensionless distance from the wall to the first grid point) was kept within the logarithmic law layer in all cases (i.e., 30 < y+ < 300). The details of each grid system applied in the grid independence study as well as the quality of the mesh are summarized in Table 1.

Type	Size Interval (mm)	No. of Cells	% of cells with skewness < 0.2	CPU Time (h)
Hexagonal	5	80,996	83.5	16.68
Hexagonal	3.2	139,140	87.8	22.68
Hexagonal	2	226,724	91.2	38.53
Hexagonal	1.25	395,224	93.4	79.35

Table 1: Mesh properties used for grid independency study.

The VOF with the implicit scheme for the time discretization and the mixture model were used to perform the air-water modelling inside the hydrocyclone. The simulations were initiated with the hydrocyclone filled with water and after formation of an axial negative pressure core the air was introduced by enabling the back flow of air via the outlets. The simulations were then continued until the full development of the air core.

The boundary conditions used in the simulations are schematically illustrated in Figure 1. At the feed inlet the velocity-inlet boundary condition was applied with the various velocities corresponding to the different mass flow rates. At the outlets, however, the pressure-outlet boundary conditions with constant zero gauge pressure was prescribed. In addition, for the multiphase modelling the backflow of air for both outlets were assigned as unity. All the remaining boundaries were set as stationary walls.

To solve governing equations ANSYS FLUENT 12.1 was used on an Intel Corei7 CPU 1.6 GHz workstation. The SIMPLE scheme coupled the continuity and momentum equations. The PRESTO algorithm was used for pressure interpolation. The modified HRIC was used for air volume fraction with the VOF model, while QUICK discretization was used with the mixture model. The momentum discretization was also computed using the QUICK method.

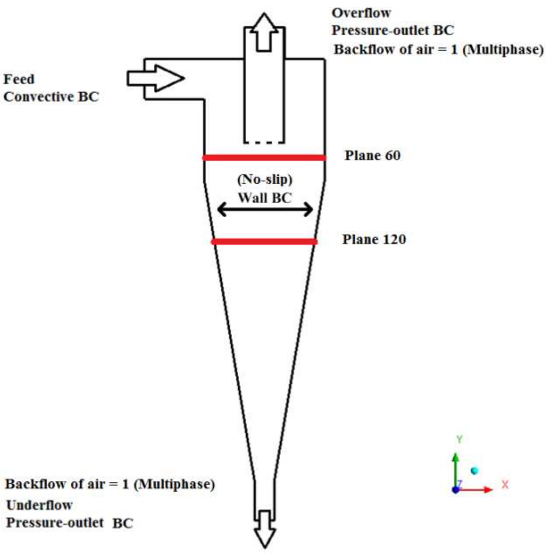

Figure 1: Schematic illustration of the boundary conditions.

RESULTS

Single-Phase Modelling

To investigate the influence of turbulence models on the numerical predictions, the RSM turbulence model with the linear pressure strain approach, and the LES turbulence model with the kinetic energy subgrid scale model are compared in Figure 2. The figure shows a plot of tangential velocity on Plane 60 (Figure 1) as a function of radial distance from the centre of the hydrocyclone. The symbols indicate the experimental measurements from Hsieh (Hsieh, 1988), the solid line corresponds to the numerical predictions for the RSM, and the dashed line to the predictions for the LES model.

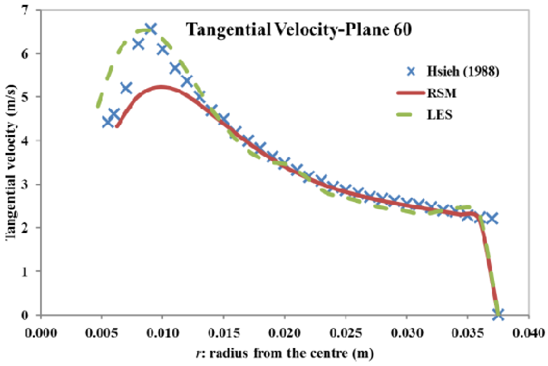

Figure 2: Comparison of two different turbulence models for prediction of tangential velocity in Plane 60.

The results show that both turbulence models are able to capture the location of the maximum and the trend of tangential velocity in Plane 60. The RSM, however, under predicts the maximum tangential velocity near the air core regions (i.e., $0.0055 < r < 0.013$) within an average difference of 12.2%, while at the same region the numerical predictions for the LES model match the experimental data very well (within and average difference of 5.5%). The computed tangential velocity for both turbulence models at the bulk region (i.e., $0.013 < r < 0.0375$) is very close to the measurements within an average difference of 1.8%, and 3.5% for RSM and LES, respectively. The slight under prediction of maximum tangential velocity for the RSM can be associated with the presence of large eddies near the air core (i.e., $0.0055 < r < 0.013$) causing more instabilities.

In order to determine the air core diameter for the single-phase modelling, the pressure distribution inside the hydrocyclone is used. It is assumed that the regions with the pressure below the saturation pressure of water at 25◦C (3169.6 Pa) resemble the air core. Figure 3 shows the pressure distribution within the hydrocyclone predicted by the RSM turbulence model for the velocity of 2.29 m/s at the inlet. The grey cylindrical-shape zone at the centre of the hydrocyclone represents an iso-surface on which the pressure is constant and equals to the saturation pressure of water. In other words, all the control volumes inside the cylinder are filled with air and the iso-surface demonstrates the air and water interface.

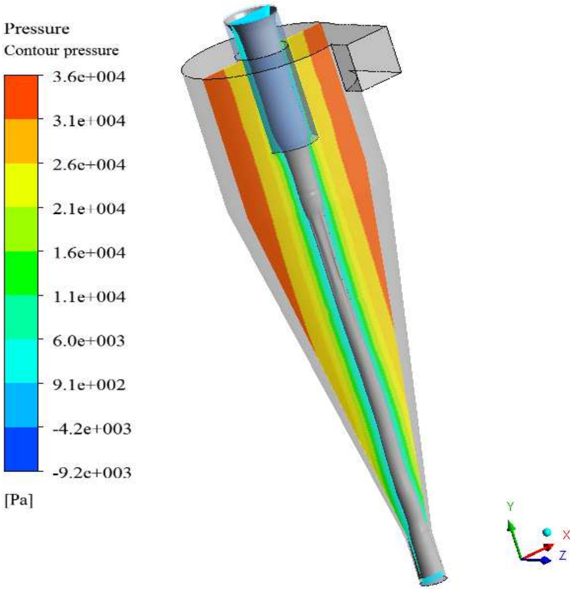

Figure 3: Pressure contour plot and the developed air core based on the single-phase modelling

As can be seen, the air core is not a cylinder with a constant diameter along the hydrocyclone, even though Hsieh (Hsieh and Rajamani, 1988) suggested a constant size air core for the entire length of the hydrocyclone. The CFD results also show that the air core diameter is greater at the two outlets compared to the other parts of the hydrocyclone. This can be attributed to the entry of air from the underflow and overflow.

The overall average of the air core diameter along the hydrocyclone predicted by two different turbulence models, RSM and LES, are 8.63mm and 10.64mm. The single-phase predictions of the air core diameter for the inlet velocity of 2.29 m/s (corresponding to 1.117 kg/s mass flow rate of Hsieh) yielded reasonably good agreement with the measurement of Hsieh within an average difference of 8.8% and 6% for RSM and LES, respectively.

Multiphase Modelling

Two multiphase models, namely VOF and mixture, are compared to study the influence of multiphase modelling choice on the numerical predictions of the air core diameter and the velocity components. In both methods the hydrocyclone is filled with water to initialize the computational domain and air is introduced after the formation of a negative pressure core at the centre. The process of the air core development for both multiphase modelling approaches is identical. RSM is used as turbulence model, since Brennan's results (Brennan, 2006) showed that using LES requires an extremely fine mesh and small time step. Besides, Delgadillo and Rajamani (Delgadillo and Rajamani, 2009) suggested that the LES turbulence model is an expensive model in computational time. Figure 4 shows the development of the air core for the VOF model over the simulation time. Since the role of the dispersed air in the feed is not considered in this study, the entire amount of air enters into the hydrocyclone from the underflow and overflow. Owing to the higher turbulent intensity at the underflow the air from this outlet can permeate into the body of hydrocyclone with the higher pace compared to the overflow as can be seen in Figure 4. Although the formation of the air core is similar for both multiphase models, there exists a slight difference between numerical predictions for each model. The global average of the air core diameter along the hydrocyclone is 8.23mm for the mixture model, while the predicted value for the VOF model equals to the measured air core diameter of Hsieh (i.e., 10 mm). The observed discrepancy between the VOF and the mixture model can be explained by their formulations for the modelling of air. The VOF model tracks the volume fraction of the air in each computational cell, whereas the mixture model considers the air phase being spherical particles with a constant diameter (in this study 0.1 mm) and uses an algebraic equation for the relative velocities between the continuous and dispersed phase.

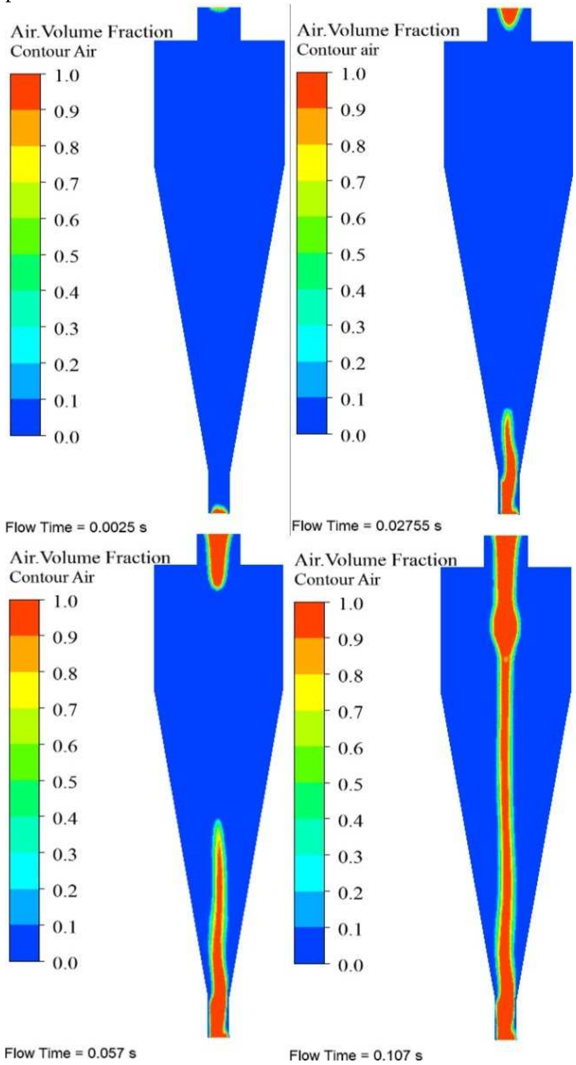

Figure 4: Air core development process.

The numerical predictions of the velocity components for both VOF and mixture model are essentially similar. But it must be noted that using multiphase modelling instead of the single-phase can enhance the agreement between the CFD predictions of velocities and experimental data. Figure 5 shows a plot comparing the single-phase and the multiphase methods for prediction of the tangential velocity on Plane 60 using RSM turbulence model. In this figure the symbols represent the measurements of Hsieh, the solid line corresponds to the tangential velocity predictions for VOF, and the dashed line corresponds to the tangential velocity predictions for the single-phase approach. The results clearly demonstrate that for the region near the air core ($0.0055 < r < 0.013$) the average percentage difference between the CFD predictions and experimental data has been improved from 12.2% for single-phase to 4.7% for multiphase model. The overall quantitative accuracy of the velocity predictions is significantly improved using multiphase modelling from 7.02% for single-phase to 0.23% for multiphase. In addition, comparison of the air core predictions for single-phase and multiphase reveals that the multiphase modelling approach improves the agreement with experimental measurement of Hsieh from 6% for the single-phase to 2.9% for the multiphase model.

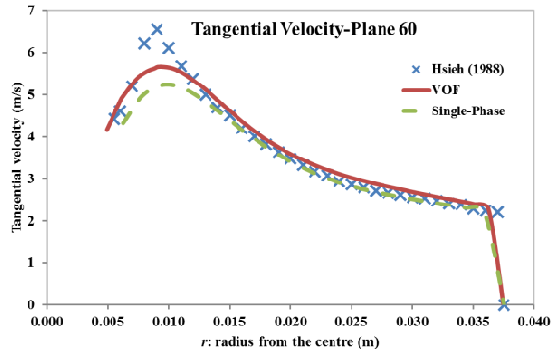

Figure 5: Comparison of single-phase and multiphase methods for prediction of tangential velocity on Plane 60.

In all of the separation theories for the hydrocyclone, feed flow rate has a significant role on the hydrocyclone performance. Therefore, in this study a parametric analysis has been performed to investigate the impact of feed flow rate on the air core diameter. Five different inlet velocities ranging from 1.45 m/s to 5 m/s (corresponding to the feed flow rate of 0.75 kg/s to 2.45 kg/s) have been investigated.

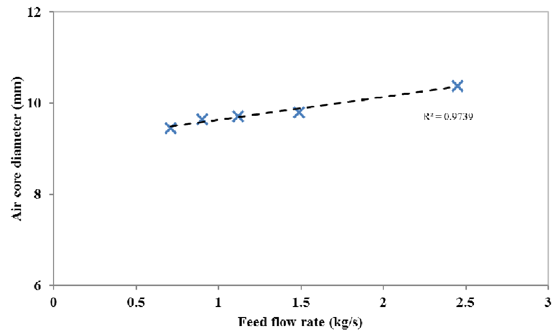

Figure 6: Numerical predictions of air core for different feed flow rates.

Figure 6 shows the numerical predictions of the air core diameter as a function of feed flow rate. In this plot the symbols represent the numerical predictions of the air core, and the dashed line corresponds to the general trend of the air core diameter for the different feed flow rates. As can be seen for the first four feed flow rates the variations in the numerical predictions of the air core are negligible. However, for the last case with the feed flow rate of 2.45 kg/s it is found that increasing the inlet velocity slightly increases the average air core diameter. The trend between the air core size and the feed flow rate is similar to the experimental findings of Gupta et al. (Gupta et al., 2008). Overall, the results from the parametric study reveal that the dependency of the air core size to the inlet velocity is insignificant except at the very high flow rates at the inlet that increase the air core size. This phenomenon may lead to the roping discharge for the hydrocyclones working at high feed flow rates. Further research is required to investigate the simultaneous effects of the feed solid percentage and its flow rate on the roping situation.

CONCLUSION

In this paper, CFD simulations of flow through a 75mm diameter hydrocyclone, adopted from Hsieh (Hsieh, 1988), were performed to account for the effect of modelling approach on the numerical predictions of the air core diameter and the velocity components. In addition, a parametric investigation was conducted to explore how feed flow rate influences the air core diameter. Using RSM and LES turbulence models for single-phase modelling revealed that both models were capable of predicting the flow field inside the hydrocyclone. However, the velocity predictions for the LES turbulence model showed slightly better agreement with experimental data. The air core modelling for the single-phase was accomplished using the concept of saturation pressure of water, and it was found that the numerical predictions of air core obtained with LES turbulence model fit the measurements better within an average difference of 6%. This suggests that one can model the flow of water inside the hydrocyclone and reasonably predict the air core diameter using the saturation pressure water in conjunction with LES turbulence model. In other words, the single-phase methodology presented in this paper is a computationally economical and practically accurate approach to predict the air core diameter.

Two different multiphase models, VOF and mixture, were compared to predict the air core diameter and velocity components. The computed velocity components for both multiphase approaches were similar. However, the predicted air core diameter for the VOF model was very close to the Hsieh's measurements within an average difference of 0.1%. Simulations at different feed flow rates revealed a linear trend between the air core diameter and the feed flow rate. Comparison of the results generated by single-phase and multiphase modelling suggested that the extra effort to include additional physics of the air phase can improve the accuracy of the numerical predictions.

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