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Simulation Studies of A 76MM Hydrocyclone

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Abstract: The investigation pertains to establishing a simulation methodology for understanding the separation characteristics of a typical hydrocyclone where the work was carried out using a commercially available CFD software. The studies included water flow profiles, water throughput & product split, particle distribution etc. and the simulated results are further validated with suitably performed experiments. The work essentially highlights the performance of the hydrocyclone using numerical studies where water is used as a primary phase and solid particles as secondary ones. This methodology is expected to be useful in the design of hydrocyclones and optimizing the processes.

keyword: CFD modeling, hydrocyclone, partition numbers, cyclone cut-size.

1 Introduction

Hydrocyclones are employed for classification of minerals and materials in a wide range of industries pertaining to mineral processing, chemical engineering, petroleum, and paper & pulp industries. Due to several advantages, such as ease of operation, high throughput, less maintenance, less floor space requirement etc., hydrocyclones have been widely accepted in the area of mineral processing. Though hydrocyclone was patented in late 18^{th} century, rigorous understanding on principles and application began only in mid fifties [Kelsall (1952, 1953)]. These studies of Kelsall on the axial, radial and tangential velocity profiles inside a cyclone formed the basis for the subsequent research. Due to several prohibiting conditions, like complex nature of the phenomenon involved, non-availability of high-speed computational systems etc., most of the research work till recent times was focused on the empirical modeling [Lynch and Rao (1975); Plitt (1976)]. With the advent of high speed computational systems, in the recent past, significant work has been reported on the simulation of hydrocyclone performance using Computational Fluid Dynamics (CFD) techniques [Hsieh and Rajamani (1986); Monredon et al. (1991); Rajamani and Milin (1992); Slack and Wraith (1997); Stovin and Saul (1998); Slack, Prasad, Baker, Boysan (2000); Slack and Wraith (2002) ; Grady, Wesson, Abdullah, Kalu (2002); Slack, Porte, Engelman (2003); Schuetz, Mayor, Bierdel, Piesche (2003); Grady, Wesson, Abdullah, Kalu (2003)]. As the numerical techniques are still under development for different applications, the simulation results need to be validated with the experimental data prior to the real use is made for design applications. We used a commercially available CFD software finding applications in hydrocyclone simulation [Slack and Wraith (1997); Slack, Prasad, Baker, Boysan (2000); Slack and Wraith (2002) ; Slack, Porte, Engelman (2003)]. Though most of these studies are related to validation of water flow characteristics, the simulated results of solids separation behavior still need rigorous validation with experimental results obtained on different geometries of cyclones meant for establishing suitable methodologies. In this paper, the simulation results carried out on a 76mm Φ hydrocyclone are validated with experimental data generated in the laboratory. The results are analyzed in terms of cyclone throughout; water split and cut size are presented.

Initially, simulation of water flow patterns inside the cyclone reported by earlier workers [Hsieh and Rajamani (1986); Slack and Wraith (2002); Schuetz, Mayor, Bierdel, Piesche (2003); Grady, Wesson, Abdullah, Kalu (2003); Slack, Porte, Engelman (2003)] were attempted. Later, the water distribution behavior for different operating conditions was simulated and compared successfully with experimental values of the water throughput and water split (percentage of the total water-report) into overflow and underflow streams, obtained after feeding water into the cyclone. Further, separation behavior of different size particles was studied using particle injection technique. The simulated results on the effects of feed inlet

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pressure and spigot opening on the partition numbers obtained for different-size-fractions are discussed and compared with the experimental results obtained by treating clay as the feed material.

2 Model description

2.1 Geometry

The hydrocyclone geometry used for simulation studies is presented in Fig. 1. The system consists of a main cylindrical body with 76mm diameter and 85 mm in length. A frustum with top diameter of 76 mm and with bottom diameter of 10mm maintained at a cone angle of 10 ° is connected to the main cylindrical body. Studies were carried out by changing the bottom diameter of the frustum at 15 and 20 mm at a constant cone angle of 10 °. A cylindrical vortex finder with an inner diameter of 25 mm and outer diameter of 40 mm protrudes into the main cylindrical body extending over a length of 60 mm inside and 30 mm above the top surface. A rectangular 20x10 mm tangential feed inlet opening is connected to the cylindrical surface at a height of 15 mm below the top surface. The geometry used in the simulation studies is presented in Tab. 1.

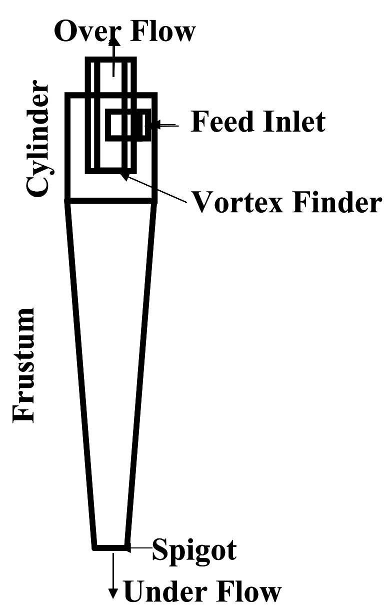


Figure 1 : Hydrocyclone Geometry

Table 1 : Design details of Hydrocyclone used for simulation

Dimensions in mm	Cyclone 1	Cyclone 2	Cyclone 3	Cyclone 4
CD	76	76	76	76
CyL	85	85	85	85
VFD	25	25	25	25
VFL	90	90	90	90
FI (l x w)	20 x 10	20 x 10	20 x 10	20 x 10
CA*	10°	10°	10°	10°
SPD	10	15	20	25

CD: Cyclone diameter; CyL: Cylindrical length; VFD: Vortex finder diameter; VFL: Vortex finder length; FI: Feed inlet dimensions (length x width); CA: *Cone angle in degrees; SPD: Spigot diameter

2.2 Meshing scheme

Hydrocyclones are not axisymmetric at the feed inlet opening and therefore it is not appropriate to model the geometry in a 2-D plane. Also, the results of the earlier researchers using a 3-D model are reported to have better agreement with the experimental data compared to that of an analysis assuming axisymmetric geometry [www.psl.bc.ca/downloads/ presentations/cyclone/cyclone.html]. Thus in the present study, simulations were carried out using a 3-D computational model. Incremental mesh densities of 50,000, 75,000, 100,000, and 150,000 computational elements were attempted to optimize the mesh density for a reasonable solution. Though the results at higher mesh densities were found slightly better, enormous computation time has become a constraint. Thus the mesh density of 150,000 computational cells was used as an optimum value for further studies on the variables. A fully unstructured grid based on tetrahedral cells with T-grid meshing scheme was used for describing the cyclone geometry. All the simulations were carried out using a P-IV machine.

2.3 Boundary and initial conditions

The cyclone body consists of an inlet for feed and two outlet products termed as overflow and underflow. Feed inlet was designated as pressure inlet. The overflow and underflow outlets were defined as pressure outlets. Water was fed into the cyclone as a primary phase with density

998.2kg/m^3 and a viscosity value of 0.001003kg/m-s. Water pressure inlet values of 55 K Pascal and 83 K Pascal were defined. The underflow outlets of 10mm, 15mm and 20 mm corresponding to the experimental conditions were varied in the simulated geometry. Inert solid particles of clay material with density 2650kg/m^3 of different size material varying between 1 and 25 μm were injected from the feed inlet boundary zone along the surface. The particles entering any of the pressure outlet zones were assigned to escape the vessel.

3 Simulation

Numerical simulations were carried out in Cartesian coordinate system. A segregated steady state 3-D double precision solver was used for simulating the flow conditions. The segregated solver solves the governing Nevier Stokes equations sequentially using iterative methods till the defined values of convergence are met. The properties of the water are used at the beginning along with the pressure and face mass fluxes for calculating the momentum equations and further update the velocity field. PRESTO (Pressure staggered option), a pressure interpolation scheme which is useful for predicting highly swirling flow characteristics prevailing inside the cyclone body [Fluent Europe Ltd (2002)] was adopted. Further, Reynolds stress model (RSM), which was reported to account with greater precision for the effects of streamline curvature, swirl, rotation, and rapid changes in strain rate with anisotropic behavior etc. [Slack, Porte, Engelman (2003)], was selected for turbulence calculations. SIMPLE algorithm scheme, which uses a combinatin of continuity and momentum equations to derive an equation for pressure, was used for pressure and velocity coupling to obtain the pressure field inside the system [Schuetz, Mayor, Bierdel, Piesche (2003)]. Higher-order Quadratic Upwind Interpolation (QUICK) spatial discretisation scheme reported to be useful for swirling flows was used for field variables interpolation from cell centers to faces of the control volumes [Fluent Europe Ltd (2002)].

Simulations were carried out for about 10,000 incremental steps where in general a preset value of convergence criteria 10E-6 was achieved.

For achieving the particle separation behavior inside the cyclone system, Discrete Phase Modelling (DPM) was adopted. This method simulates the particle trajectory in a Lagrangian frame of reference. Stochastic tracking model was adopted for the dispersion of particles due to turbulence in the primary phase. It includes the effects of instantaneous velocity fluctuations during prediction of particle trajectories.

4 Experimental

The test rig used in the experimental work (Fig. 2) consisted a feed slurry tank of 200 liters capacity mounted on a stable platform. The bottom of the feed tank was connected to a centrifugal pump driven by a 3-phase, 5.5 kw motor. The outlet of the pump was connected to the feed inlet of a 76mm hydrocyclone. A by-pass pipe with a control valve was connected to the pump outlet line to maintain the required pressure drop inside the cyclone. A diaphragm type pressure gauge was fitted near the feed inlet to indicate the pressure drop. The hydrocyclone was positioned vertically above the slurry tank.

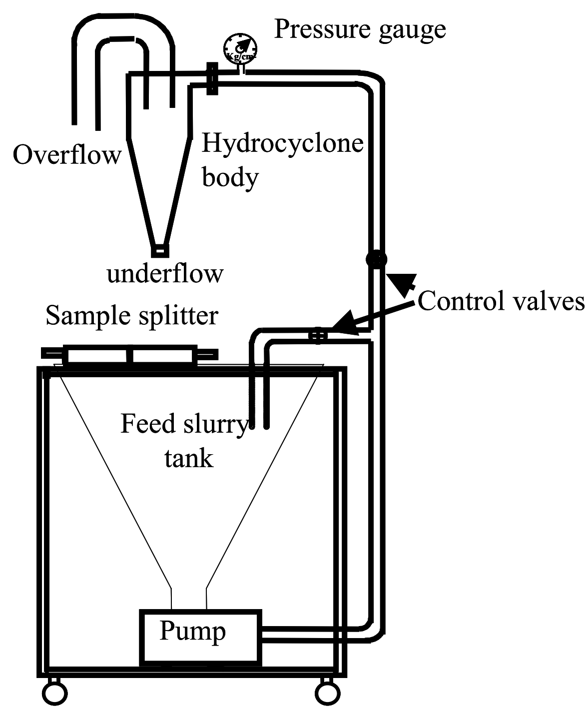


Figure 2 : Hydrocyclone experimental test-rig

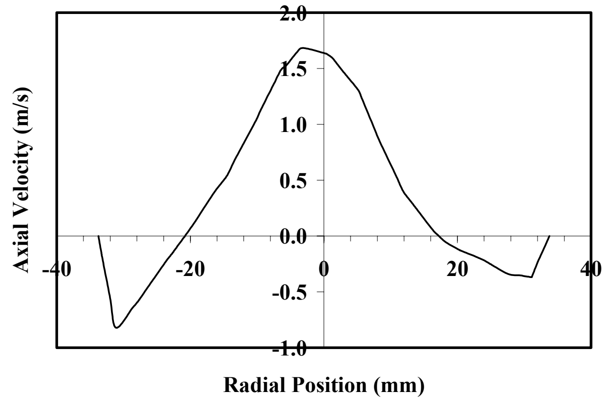
In the experimental design, the levels of spigot opening and feed inlet pressure were selected to generate a wide range of water splits into the overflow and underflow products. Required size spigot as per the experimental design was fitted to the cyclone after fixing the main body to the test-rig. In the water-distribution studies, water was pumped into the cyclone at different spigot openings and feed pressures. While experimentation with slurry samples, measured amounts of solids and water were mixed in the feed tank to achieve a solids consistency of 10% by weight in the feed pulp. The slurry was pumped into the cyclone at desired feed pressure and at different spigot openings. Timed samples of overflow and underflow products were collected separately. The underflow and overflow samples were filtered, dried and weighed. Representative samples of the dried material were analyzed for particle size distribution using a Malvern laser particle size analyzer. From the size analysis data, distribution points (percentage report of each size fraction in the feed to the underflow product) are generated.

5 Results and Discussion

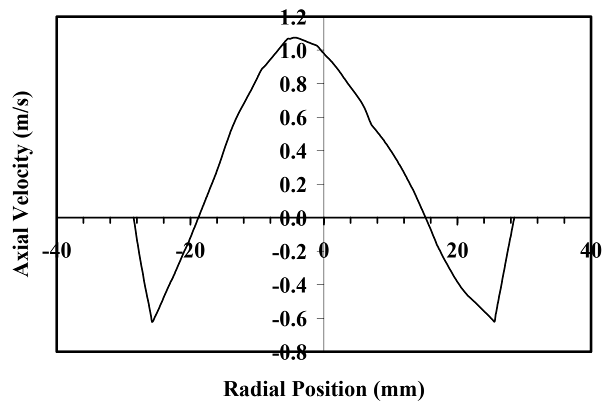
While treating water in the cyclone, information on the cyclone throughput (total flow rate of water passing through the cyclone obtained by adding mass flow rate through overflow and mass flow rate through underflow), and on the water-split (percent report of total water entering the cyclone) into overflow product were used for validating the predictions at different test runs with the experimental values. The simulation studies were carried out at three spigot openings, i.e. 10mm, 15mm, and 20mm and at two feed inlet pressures of 55 K Pascal and 83 K Pascal. The results obtained are discussed in three stages. Initial discussions cover the simulated general flow behavior inside the system. Later, the simulated results of mass throughput and spilt of water to over flow are discussed specifically validating with the experimental data. Finally the distribution curves obtained during simulation study are compared with the experimental data at all the test conditions.

5.1 General flow behavior

The general flow behavior in terms of velocity distributions at different planes inside the system are discussed with qualitative comparison of the published flow profiles of hydrocyclones [Hsieh and Rajamani (1986); Slack and Wraith (2002); Fluent Europe Ltd (2002); Slack, Porte, Engelman (2003); Slack, Porte, Engelman (2003)].



(a) Vertical position 125mm

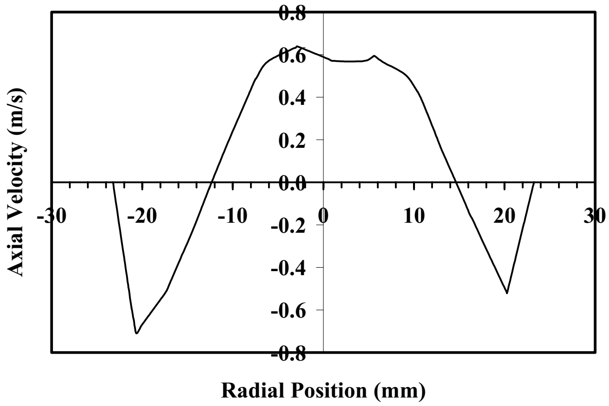


(b) Vertical position 175mm

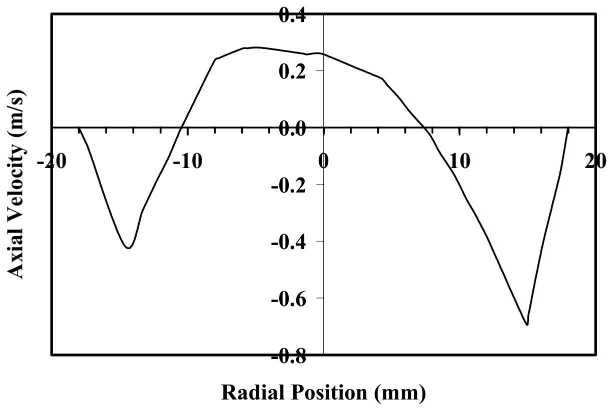
Figure 3: (a) and (b)

5.1.1 Axial velocity

The results obtained on the axial velocity distributions in different X-Y planes at different positions, are shown in Fig. 3(a) through Fig. 3(d). From the figures it can be observed that a maximum positive axial velocity values indicating a vertically upward flow exists at or very near the cyclone axis. With the increasing radial distance, this value decreases till it reaches zero at some distance away from the cyclone axis. With a further increase in the radial distance, negative axial velocity indicating a vertically downward flow begins. This observation can be made at all the heights inside the conical body. A maximum negative axial velocity was observed at some radial distance away from the cyclone wall. A compari-



(c) Vertical position 225mm



(d) Vertical position 275mm

Figure 3 : Axial velocity at different vertical positions inside the cyclone

son of these figures also indicates that the peak value of positive axial velocity is maximum immediately below the bottom of the vortex finder (Fig. 3(a)) and minimum at or near the spigot opening (Fig. 3(d)).

Fig. 4(a) and Fig. 4(b) indicate that along the cyclone height there are concentric layers of similar axial velocities. The figures also indicate both the positive and negative axial velocity profiles.

5.1.2 *Tangential velocity*

The tangential velocity plots of the simulated results in X-Y planes at different vertical positions are shown in Fig. 5(a) to Fig. 5(d). The figures indicate that the tangential velocity initially increases with the radial po-

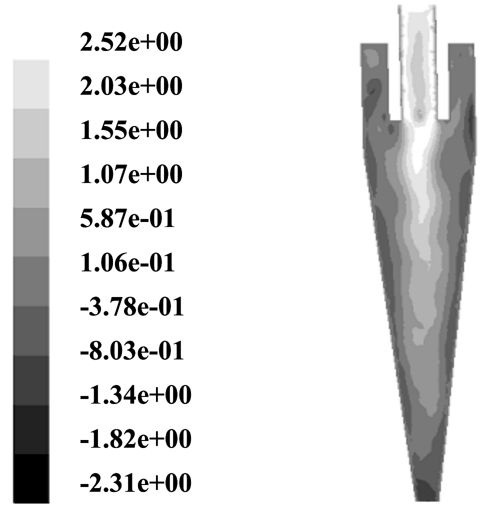


Figure 4a : Contours of axial velocity (m/sec) in axial plane

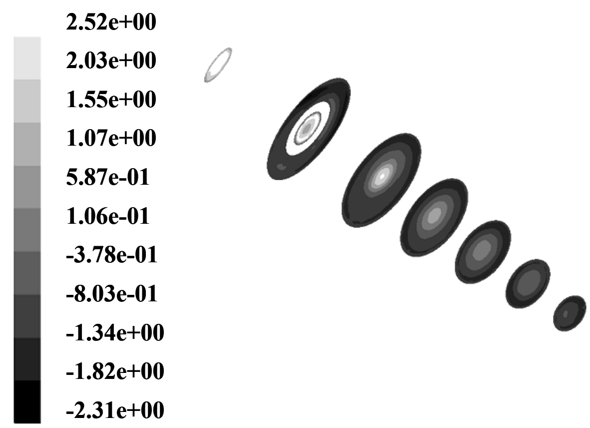
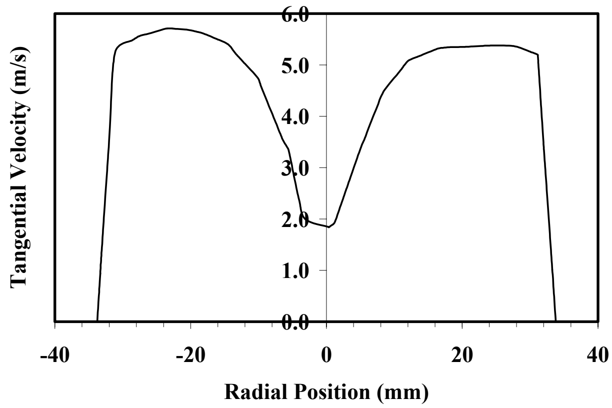
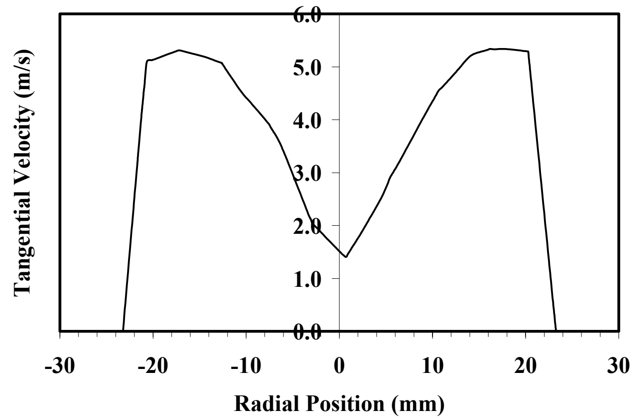


Figure 4b : Contours of axial velocity (m/sec) in radial planes

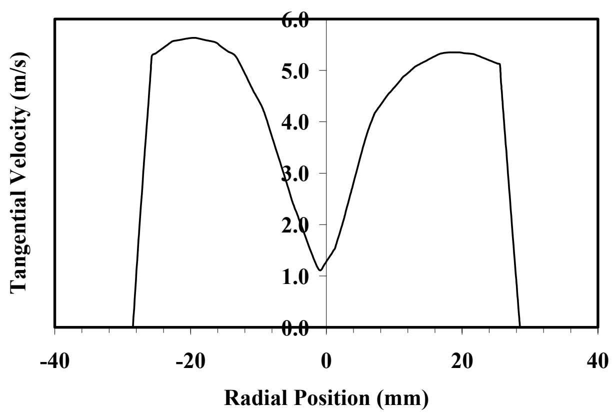
sitions till a particular value and then decreases. The published reports [Monredon et al. (1991); Slack et al. (2002)] also indicate that the tangential velocity increases sharply with radius in the central core region under the vortex finder and that thereafter decreases with radius. A comparison of the figures indicate that the tangential velocity pattern remains more or less similar while the values for maximum tangential velocity decrease with increase in the axial distances of the cyclone body.



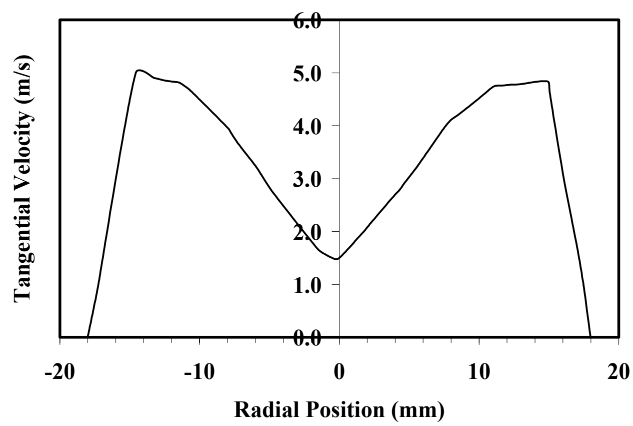
(a) Vertical position 125mm



(c) Vertical position 225mm



(b) Vertical position 175mm



(d) Vertical position 275mm

Figure 5 : Tangential velocity at different vertical positions inside the cyclone

5.2 Validation results

The results obtained on the water throughput and water split as well as the particle separation behaviour under similar experimental conditions is compared with the simulated results. The results are discussed in the following sections.

5.2.1 Water throughput

Water throughput in hydrocyclone is defined as the water flow rate through the system (experimentally obtained by adding mass flow rate through overflow and underflow). In the present study the results on the water throughput values obtained in a 76mm Hydrocyclone during the experimental work at different pressures and spigot openings are compared with the simulated values under similar conditions. The simulated and the experimental results are presented in Fig. 6. The figure indicates that the simulated results match with the experimental results with marginal error of about 4 to 8%.

5.2.2 Water split

Water split in hydrocyclone is defined as the percentage of the water throughput reporting to over flow. The simulated results are compared with the experimental data in Fig. 7. The figure indicates the relation between percentage water report to over flow and the spigot diameter. It can be observed from the figure that at the widest spigot opening the prediction is slightly higher than the exper-

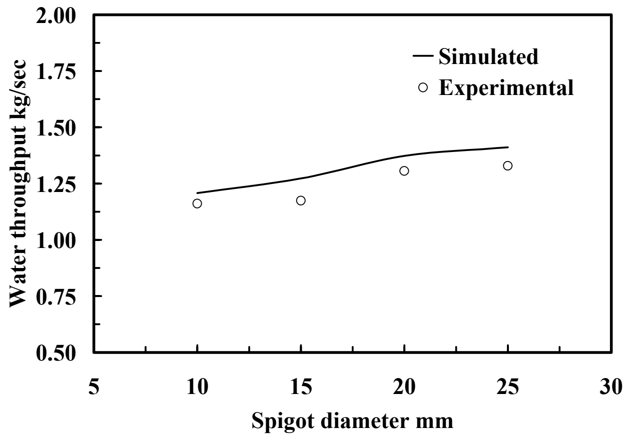


Figure 6 : Experimental and simulated data on water throughput.

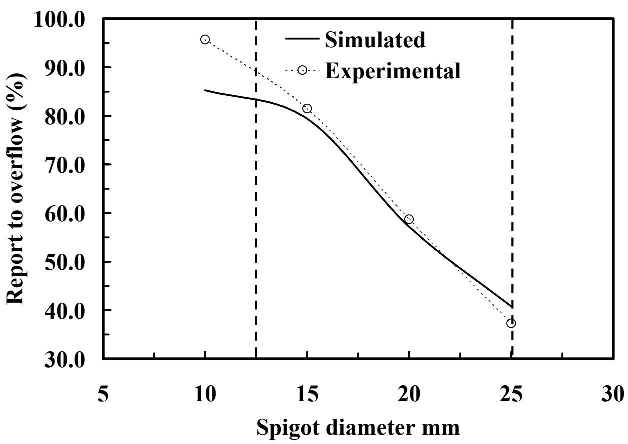


Figure 7 : Experimental and simulated results on water split

imental values where as at smallest spigot opening the simulation prediction is lower than the experimental results. However, at intermediate spigot openings the data points indicated good match with the experimental data. The dotted line enclosed the region, which corresponds to water split range of 45% to 87% in the overflow product. In this region the simulated data agrees well with the experimental results with a reasonable accuracy. The general range of water splits in a normal operating hydrocyclone will be within this region of good prediction limits.

5.3 *Particle Separation Behavior*

Particle separation behavior inside a hydrocyclone system is reported in terms of distribution or partition curves [Wills (1997)]. A typical partition curve represents the percent report of any size material in the feed into the underflow product (this number is also referred as distribution point or partition number).

It is reported that while the percentage of solids in the secondary phase is below 10% by weight, particle-tracking approach is a useful technique for efficiency prediction of separation systems [Stovin and Saul (1998)]. In the present study, for understanding the separation behavior of hydrocyclone, particles of different sizes are injected into the cyclone body from the feed inlet point after achieving the convergence for the primary phase (water) using discrete phase model. At each run a group of 1000 particles of same size and density of 2650kg/m^3 were injected into the cyclone along the face of the inlet opening. The particles report into the overflow and underflow outlet streams for a set of 10 sample runs were averaged for obtaining the partition number for each size. The exercise was extended for different sizes.

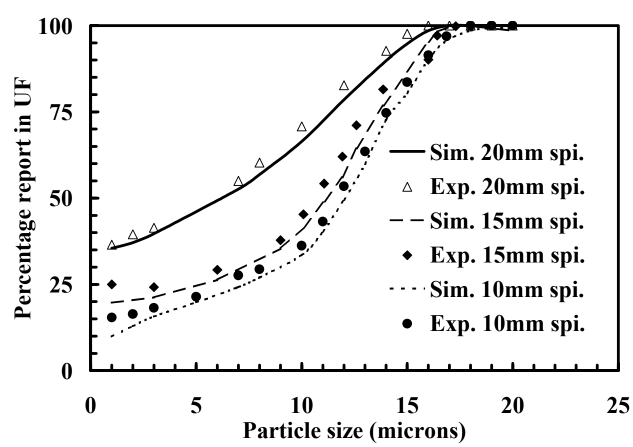


Figure 8 : Experimental and simulated partition numbers at different spigot openings and at 55 K Pascal feed pressure

The partition curves generated at 10mm, 15mm, and 20mm spigot openings at a feed pressure of 55 K Pascal using different partition numbers, are presented in Fig. 8. Also presented in the figure are the experimental values obtained under similar conditions. It may be observed that the simulated data points are reasonably matching with the experimental values at all the test conditions. Similar observations are also made at other test conditions carried out at 83 K Pascal (Fig. 9). Further, the cut size of the cyclone (d_{50}), which is the size of the particle having a partition value of 50% (report into the underflow product) of the simulated and experimental conditions are presented in Tab. 2. The data also indicates that the predicted values are closely matching with the experimental results. The data also indicates that at lower spigot openings and at lower feed pressures, the cut size increases. The observation may be attributed to constriction for material flow through the reduced spigot opening and to lower centrifugal forces on particles at lower feed inlet pressures that relatively coarser material might have reported into the overflow product.

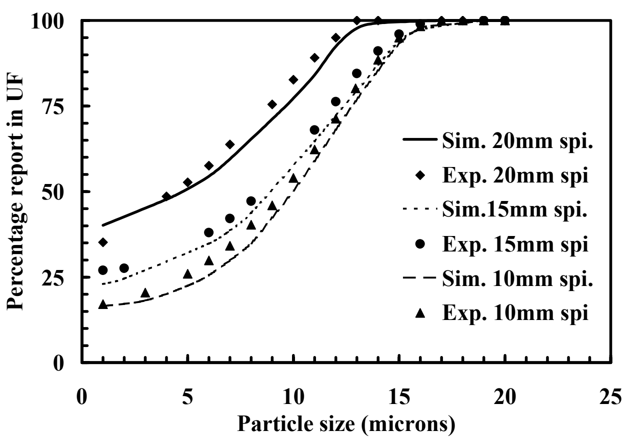


Figure 9 : Experimental and simulated partition numbers at different spigot openings and at 83 K Pascal feed pressure

6 Summary

A CFD simulation and supporting validation study on 76mm hydrocyclone have demonstrated the applicability in the analysis of the water throughput and splits for various test conditions. The simulation uses discrete phase modeling technique and found matching with the experimental results with a reasonable accuracy. The study has indicated that a methodology adopting a steady state 3-D model with Reynold's Stress approaches for turbulence along with discrete phase modeling can be adopted for predicting the performance of hydrocyclones with reasonable levels of accuracy at dilute solids concentration.

Table 2 : Experimental and simulated cyclone cut size values at different test runs

Test run	FP (Pascal)	SPD (mm)	Cut size d_{50} (microns)	
			Exp.	Sim.
1	54606	10	11.4	14.0
2	54606	15	10.8	12.0
3	54606	20	5.8	6.3
4	82737	10	9.5	10.0
5	82737	15	8.3	8.9
6	82737	20	4.5	4.9

FP: Feed pressure; SPD: Spigot diameter; Exp.: Experimental; Sim.: Simulated

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