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Computational and experimental study of the effect of inclination on hydrocyclone performance

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ABSTRACT

In this paper, the effect of inclination on hydrocyclone performance is studied using both computational fluid dynamics (CFD) and experimental methods. Experiments with water medium and the corresponding water–air two-phase CFD simulations in a 75 mm diameter cyclone are carried out at various inclined positions to the vertical plane. The two-phase CFD flow analysis shows that the water split to underflow decreases as the inclination increases, which is consistent with the experiments. The predicted flow velocity profiles were analyzed for different inclinations. An increase in the inclination results the air-core size reduction and reduced pressure drop profiles. Experimental classification also performed using the silica slurry. The experimental analysis shows the increased cut-size and the reduced water split with the inclination. Cross validation of inclined cyclone's CFD data is attempted with Electrical Resistance Tomography (ERT) and High speed video imaging experiments. The inclination effect on hydrocyclone flow field is further analyzed in terms of turbulence parameters; turbulent intensities, and radial RMS velocities. Turbulent dispersion of the particles is calculated using the CFD data and plotted by using a dispersion index formulation. Fish hook phenomena and possible mechanism of particle classification under the influence of inclination is also explained. Experimentally measured cut size and water recovery to underflow for 10 wt% silica slurry at various inclinations are compared with numerical predictions. Predicted efficiency curves are found in a close agreement with experiments for all the inclinations.

1. Introduction

Vertical hydrocyclones are very common in most of the comminution circuits. Horizontal cyclones can be found in extreme cases, which are for installation convenience rather than for process reasons. Inclined cyclones are also found for specific mineral processing applications. In coal preparation plants, dense medium cyclones are usually operated near to horizontal inclination of 20° to allow large spigot sizes for sinks removal and self-drain of contents during shutdown [1,2]. In the phosphate removal, dense medium cyclones are inclined with an angle between 0° and 90° for better separation of ore and tailings [3]. Even in the clusters, hydrocyclones are mounted with an inclination (15–20°) around the feed distributor for uniform distribution of slurry and common underflow collection. It is believed in mineral processing industry that inclined cyclones would fetch the benefit in a number of ways while classifying the solid particles by size. It is believed that gravity influences the cyclone performance by changing the air-core size and position in large cyclones to some extent [4]. It also favors the cyclone operation at coarser cut points without varying any other design and operating parameters. It is also learnt from industrial practices that minimum fines misplacement to the underflow can be achieved with an inclination to vertical position. Despite industrial practices of inclined cyclone operations, the fundamental reasons behind these changes are not clearly understood. A detail fluid flow and particle separation analysis with respect to inclination effect would fetch a better understanding on cyclone performance.

2. Literature review

2.1. Inclined cyclones

Usage of horizontally oriented cyclones in place of vertical position has shown increased efficiency by reducing short circuit flow of fines to underflow in the past. This results in reduction of circulating loads on tumbling mill [5,6]. Similar observation was found with 45° inclined cyclones by Johnstone and Rais [7]. Enhanced hydrocyclone efficiency was observed when it was operated at low inlet pressures and oriented in the horizontal position [8], and it was believed to be due to reduction in water recovery to

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the underflow. Asomah and Napier-Munn [4] have conducted experiments on various sizes of hydrocyclones (102–508 mm) at different inclinations (0–120°). Their results show that an inclination of 45° or greater has a significant effect on the performance of large diameter hydrocyclones at low pressure operations. The reported observations include the increase of cut size with inclination. Further Asomah and Napier-Munn [4] have developed an empirical model for hydrocyclones with the inclusion of feed size, viscosity and inclination as the key variables along with other standard design and operating conditions. Rong and Napier-Munn's [9] investigation on inclination (0–180°) effect on 200 mm JK classifying cyclone reveals that there was an improvement in sharpness of separation of the cyclone from vertical to horizontal position; thereafter, i.e., beyond 90° inclinations, it reduced significantly to a low value. These inclination results on the flow ratio reduction and the improvement of solids percentage in the underflow were found similar to Asomah and Napier-Munn studies [10]. Inclination effect on small hydrocyclone (75 mm) has been studied by Banisi and Deghan-Nayeri at dilute solid concentrations [11]. It was concluded that there won't be considerable change in the performance of hydrocyclone for low solids concentration (10 wt%) with the inclination. But a significant increase in the cut size was observed when cyclone operated beyond 45° inclinations for concentrated slurries. This inclination data was fitted with the empirical model proposed by Asomah and Napier-Munn [10] and an error of 6.6% for the predicted cut sizes was observed. Neither of these studies has focused on high inlet pressures and high percentage of feed solids effect at different inclinations on the performance of hydrocyclone. Although two mathematical models [4,12] have been developed considering the inclination effect for hydrocyclone based on semi- empiricism but the fundamental reason behind this inclination effect in terms of flow field and particle force field are unaddressed.

2.2. CFD modeling of hydrocyclones

Computational fluid dynamics (CFD) technique is already proven as an efficient tool for flow field and separation performance predictions of hydrocyclones [13–16]. The flow in hydrocyclone is highly complex, swirling, and turbulent in nature. This also involves a number of solid phases along with water and air-core. Therefore, usage of suitable turbulence and multi-phase models are very important. Initial numerical modeling work on hydrocyclones during 1980–90s involve 2D geometries, simple turbulence models such as Prandtl mixing length model, k–ε, Re-Normalization Group (RNG) k–ε models [14,17–20]. k–ε, RNG k–ε models are limited for simple flows and are not suitable for highly swirling turbulent flows that usually occur in hydrocyclones because of unrealistic assumptions of isotropic turbulence [21]. Reynolds Stress Model (RSM) solving individual stresses were having good predictions with the experiments [15,22,23] compared to k–ε, RNG k–ε models. Cullivan et al. [13] used RSM model with quadratic pressure strain for accurate prediction of air-core. Predictions were compared with the air-core measured by non-intrusive electrical impedance tomography technique and found in good agreement. Wang et al. [24] used RSM, volume of fluid (VOF) to model the air-core and Lagrangian multiphase model for motion of limestone particles in a 75 mm Hsieh hydrocyclone. Kuang et al. [25] studied the effect of coal feed solids concentration on 225 mm hydrocyclone performance using RSM turbulence model, Algebraic Slip Mixture (ASM) model with a modified drag, viscosity by kinetic theory [26]. The simulated coal fine particle recovery fraction to underflow found close to the underflow water-split that was reported with the literature [27]. Davailles et al. [28] also studied the effect of feed solids concentration on the performance of 100 mm hydrocyclone with Eulerian–Eulerian multiphase model coupled with RSM turbulence model. They observed the cut size (d_{50c}) improvement with increase in concentration. Reduced classification efficiency was observed at high concentrations (50%) due to increased viscosity levels and rendered particle settling velocities under the centrifugal action in hydrocyclone. Drastic reduction in the tangential velocity profiles explains the separation behavior. Even though RSM model does not simulate the fluctuating velocity components accurately with an inherent equilibrium turbulence assumption in particular to sub grid scale modeling, it was able to predict reasonable velocity profiles with low computation power.

Most of the energy and the momentum transfer of turbulent flows is associated with large eddies. By resolving the large scale eddies and modeling the small scale eddies, large eddy simulation (LES) model can able to simulate highly swirling flows accurately. LES coupled with VOF model was adopted for accurate prediction of the air-core and velocity fields for hydrocyclones[15,29,30]. Slack et al. [15] modeled the turbulence in 205 mm cyclone using both RSM and LES turbulence models and compared the predicted axial and tangential velocity profiles with experimental Laser Doppler Anemometer (LDA) measurements [31]. They concluded that RSM provided very good results at steady state with a coarse mesh and with less computational cost. On the other side LES predictions reveals time dependent vortex oscillations which can impact the separation efficiency. Delgadillo and Rajamani [29] compared the predicted values of air-core diameter, mass split, tangential and axial velocities of a 75 mm hydrocyclone with three different turbulence models; RNG k–ε, RSM and LES. LES was associated with better values to experiments [19] even though it takes high computation time. Narasimha et al. [32] predicted the air-core diameter and shape by using LES, RSM turbulence models coupled with VOF multiphase model for various spigot and vortex finder sizes. In all the cases LES was associated with better predictions of pressure and velocity field to the experimental Hsieh [19] measurements due to improved prediction of turbulence field. Brennan et al. [33] modeled the multi-phase CFD simulations of the Hsieh's cyclone [19] using the mixture model with the granular options in Fluent™ to predict the classification and the distribution of limestone inside the cyclone. They explained the origin of short circuit flow through mixing in the entrance of flow near vortex finder. Recent studies by Narasimha et al. [34] also used the modified mixture model with lift forces and Newtonian viscosity model corrected with fines to predict the particle size segregation inside the Renner's hydrocyclone [35].

In this paper, the effect of inclination on hydrocyclone performance is studied using both CFD technique and experimental methods. Experiments with water medium and the corresponding water–air two-phase CFD simulations in a 75 mm diameter cyclone are carried out at various inclined positions to the vertical plane. Classification experiments also performed using the silica slurry and the corresponding multi-phase simulations were also conducted at various cyclone inclinations. Inclination effect on the flow analysis of hydrocyclone w.r.t mean and turbulent flow field, flow split, air-core size and position, and particle turbulent dispersion is investigated. Basic reasons behind the cyclone incli-

Table 1
Range of variable conditions used to study the inclination effect.

Variable	Variation
Inclination (°)	0, 30, 45, 60
Pressure (kPa)	35, 69, 103.5, 138, 175
Concentration (wt% of feed solids)	0, 10, 28.76, 50
Vortex finder diameter (mm)	18, 25
Inlet diameter (mm)	45
Spigot diameter (mm)	12.5, 15
Cyclone diameter (mm)	75