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Numerical and experimental examination of swirl flow in a cylindrical container with rotating lids

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Abstract

Swirl flow is the primary mechanism for separation of particles in a hydrocyclone and hence influences the performance. The study of examining the basic swirl flow mechanism is accomplished by using a cylindrical apparatus with rotating lids. The upper and lower lids of the cylinder are able to rotate in the counter and clockwise direction at different angular velocities. In this study, the basic mechanisms of swirling in the laminar regime are investigated using an optically clear cylinder with rotating lids. The cylinder is filled with a liquid and the upper and lower lids of the cylinder are allowed to rotate in the clockwise and counter-clockwise directions. The induced flow is measured with a laser doppler anemometer and is compared to the velocity predictions from an in house developed software which solves the equations of motion. The results presented here constitute the first step in a series of experiments with the ultimate goal to improve the separation mechanism of hydrocyclones by means of controlling swirling flow characteristics.

Keywords: Hydrocyclones; Computational fluid dynamics; Laser doppler anemometry

1. Introduction

The internal swirling flow pattern is a complex flow feature that is of interest in various industrial applications. Depending on the application, swirling flow increases mixing, improves heat conduction, or creates a centrifugal force that is used for separation. Consequently, such flows are used in a large range of devices such as heat exchangers, turbines, combustion equipment and separators using centrifugal effects, such as cyclones and hydrocyclones. Basic swirl flow phenomenon has been studied experimentally for a variety of flow regimes (Talbot, 1954; Faler and Leibovich, 1977; Escudier, 1984, 1988; Gupta et al., 1984; Alekseenko et al., 1999; Lim and Cui, 2005). These studies allowed observation of quasi-periodic oscillations described as vortex core procession, sub-critical flow, and vortex breakdown phenomena. Theoretical models shed some light on the explanation of instability mechanism of swirling flows (Wang and Rusek, 1996). There have also been various attempts to numerically simulate internal and turbulent swirling flows. In previous numerical models, the tangential component of flow has been created using: axially rotating pipe wall (Orlandi and Fatica, 1997), a swirl tube with a tangential inlet (Derksen, 2005), rotating channel flow with moving boundaries (Bech and Andersson, 1997), or special geometries as in combustor chambers (Chen and Lin, 1999). The shape of recirculation zones has been experimentally characterized by Nissan and Bresan (1961) and Sheen et al. (1996) and the swirl decay has been numerically predicted by de Farias Neto et al. (1998).

The research originated in this paper was motivated by authors' earlier work on hydrocyclones. In hydrocyclones, the centrifugal force, resulting from swirling flow, is responsible for the separation mechanism for particles or

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droplets from liquid–solid or liquid–liquid mixtures. The slurry is injected into the hydrocyclone via one or several tangential inlets. The combined axial and tangential components of velocity field characterize a flow streamline that rotates around the axis. The wall curvature directs the flow into a spiral path that travels downwards towards the apex, as shown in Fig. 1.

While the wall friction reduces the tangential velocity, the contraction in the geometry maintains the magnitude of the velocity. The heavy particles in the suspension travel towards the hydrocyclone wall and then down to the apex. In the conical contraction section, an axial reversal flow is formed and moves upwards through the vortex finder. Similar separation mechanism is used in vortex settling basins (Athar et al., 2003).

Although hydrocyclones have been used in industry since the 1950s, the details of the flow behavior is still not well understood. Modelling and experimental investigation of the complexity and range of phenomena of fluid flow in a slurry separator has been attempted for many years and is presented in numerous scientific contributions (Doby et al., in press). The nature of fluid flow and in particular its swirling character has been studied experimentally by Fisher and Flack (2002), theoretically using computational methods by Nowakowski et al. (2004), or simplified analytical approaches with the most extensive presented by Bloor and Ingham (1987). All these strands of the research confirm that a vortex constituting a swirl flow is composed of two separate vortices, a free and forced. A forced vortex resembles a solid body rotation. Near the wall, the swirling components become less dominant and the device geometry plays a more significant role. The relationship between the tangential velocity and the radius is inversely proportional in the free vortex and proportional in the forced vortex. Although this phenomenon seems to be obvious, it is intuitively understood and is observed in prevalent studies, there are some uncertainties

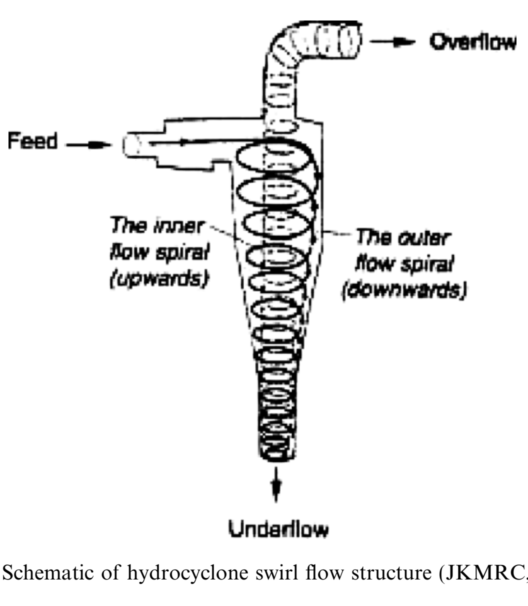

Fig. 1. Schematic of hydrocyclone swirl flow structure (JKMRC, 1999).

related to how the swirl flow could be controlled. Detail investigation of the velocity patterns in various flow regimes may provide a fruitful avenue for understanding a number of open issues regarding internal swirling flow and the implications on separational efficiency of hydrocyclone. Evidence shows that the fluctuating motion in the presence of swirl is anisotropic and invalidates some of the assumptions on which simple turbulence models are based. As a result lower-order turbulence models have not been able to successfully handle effects of streamline curvature (Bradshaw et al., 1996). These shortcomings have been recognized and increased accuracy computational models have been applied. Representative studies in this area include application of a second-order differential stress model by Cullivan et al. (2003) and large eddy simulation (LES) (Slack et al., 2000; Delgadillo and Rajamani, 2005). Such simulations can capture asymmetry of time-dependent vortex oscillations and non-equilibrium turbulence.

The comprehensive study on swirl flow could help understanding the physics behind separation in hydrocyclones. There are several reasons to conduct such study. The main arguments are reiterated. (i) The method of generation of helical vortices with swirl flow directly effects the efficiency of hydrocyclone (Gupta et al., 1984). (ii) The characteristics of the flow field in a hydrocyclone depend on the radial, angular, and axial position since the swirl flow is decaying (Shi and Chehroudi, 1994). It is important to be able to control these characteristics. (iii) The complex flow structure invalidates some of the assumptions behind standard turbulence models, which are usually tuned and validated for simple flows (Jakirlic et al., 2002). The absence of spectral gap between coherent and turbulent fluctuations makes LES simulation a favorable option, but perhaps not always possible for industrial applications. Therefore, the challenge to practically model a hydrocyclone is very difficult without compensating for this lack of information.

The paper investigates the swirl flow mechanism in a cylindrical container. The construction of apparatus enables the lids to be rotated. Due to shear forces, the rotation of the lid induces a flow field on the fluid. The test environment both numerical and experimental was created to conduct a flow pattern analysis. This allows validation of the numerical results and verification of experimental technique before replacing the cylindrical container with specially constructed hydrocyclone. The results presented here constitute the first step in a series of experiments with the ultimate goal to improve the separation mechanism by means of controlling swirling flow characteristics in hydrocyclones. The relatively simple container geometry helps to identify errors in measurements and data analysis. The approach, although starting with laminar flows, allows evaluation of swirl flow at high Reynolds numbers. This enables incremental changes in the vortex structure to be studied and could help to understand when the fluid develops into unsteady 3D flow. In longer term the setup will be