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Numerical analysis of hydrocyclones with different conical section designs

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ABSTRACT

Hydrocyclones generally follow a conventional design and may have some limitations on separation performance. This paper presents a numerical study of hydrocyclones with different conical configurations by a recently developed computational fluid dynamics method. The feed solids concentration considered is up to 30% (by volume), which is well beyond the range reported before. The numerical results show that the cyclone performance is sensitive to both the length and shape of the conical section, as well as the feed solids concentration. A longer conical section length leads to decreased inlet pressure drop, cut size d_{50}, and Ecart probable E_p, and at the same time, an increased water split (thus larger by-pass effect). When conical shape varies from the concave to convex styles gradually, a compromised optimum performance is observed for the cyclone with a convex cone, resulting in a minimum E_p and relatively small inlet pressure drop and water split. Almost all these effects are pronounced with increasing feed solids concentration. Based on the numerical experiments, a new hydrocyclone featured with a long convex cone is proposed. It can improve the performance of the conventional cyclone at all the feed solids concentrations considered.

1. Introduction

Hydrocyclones are widely used to classify solids by size in many industries due to their design simplicity, high capacity, low maintenance and operational costs. However, there are different problems associated with such a separator, such as high energy loss, misplaced particles in both the overflow and underflow, and limited sharpness of the cut in particle sizes between the fine and coarse streams. To date, how to overcome these problems is still a challenge.

The structure of hydrocyclone affects cyclone performance depending on operational conditions and materials to be handled. Such effects should be known for practical applications of hydrocyclones. In this respect, various studies have been carried out in the past to investigate the flow and performance of hydrocylones with different conical configurations. For example, based on studies of a series of variables, Fontein et al. (1962) suggested that the conical section should be as long as possible, but the cylindrical section is retained for the purpose of providing a convenient feed opening, especially in small cyclones. Similarly, Svarovsky (1984) reported that the cylindrical section may be short or even omitted, whereas the conical section is essential. Chiné and Concha (2000) compared the conical and cylindrical hydrocyclones and revealed that the tangential velocities of the liquid phase within the two cyclones are similar but the axial velocities are different. Chu et al. (2000) assessed different structural modifications and showed that the modification of conical part affects the cyclone performance. In that work, two specific conical shapes were considered and it was found that both the concave and convex designs lead to increased separation sharpness and cut size, compared to the conventional design. However, only the convex design caused a decreased energy loss and flow split. Chu et al. (2002) also observed that the particle radial velocity, which determines the separation efficiency, is higher for a hydrocyclone with a conical section of longer length, at a given cone angle. Recently, Wang and Yu (2006) quantified the effects of conical section length and other geometrical variables on separation efficiency and flow characteristics. Their results confirmed the importance of conical part as reported by Fontein et al. (1962) and Svarovsky (1984). Yang et al. (2010) introduced a two-cone combination instead of the conventional single cone, and showed that the modification can lead to a better hydrocyclone performance. All these studies mainly based on experiments, suggest that a better design of the conical part should be beneficial to the cyclone performance. However, most of them focused on operations at low feed solids concentrations. To date, the effects of the conical part on the flow and performance of hydrocyclones are not clear, particularly when

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hydrocyclones are operated at different feed solids concentrations as widely used in practice (see, e.g., Slechta and Firth, 1984; Dyakowski and Williams, 1996; O'Brien et al., 2000; Hararah et al., 2010; Zhang et al., 2011). Also, systematic studies of geometrical variables including those related to the conical part are lacking. Usually, hydrocyclones are designed on the basis of empirical models. The most widely known model would be that of Plitt, which however may be unbound to practical limits and yield unrealistic results (Svarovsky and Thew, 1992). In principle, these problems can be overcome by numerical simulations which are often carried out under well controlled conditions for a wide range of applications.

In recent years, various numerical studies have been done for better designing and controlling hydrocyclones (see, for example, the reviews by Nowakowski et al. (2004) and Narasimha et al. (2007). The numerical models were mainly based on CFD-LPT (Computational Fluid Dynamics-Lagrangian Particle Tracking) and TFM (Two-Fluid Model) approaches. In the former, the motion of discrete particles is obtained by LPT which applies Newton's laws of motion to a particle, and the flow of continuum fluid is described by the local averaged Navier–Stokes equations that can be solved by the traditional CFD. However, it traces only the motion of a single particle, and the effect of inter-particle interactions and the reaction of particles on the fluid are ignored. Therefore, although widely used in the previous studies, CFD-LPT is applicable only to dilute-phase flows or very low feed solids concentrations, hence has significant limitations in applied research.

In the TFM approach, on the other hand, both the fluid and solid phases are treated as interpenetrating continuum media at a computational cell scale that is much larger than individual particles but still smaller compared to the size of the process equipment. Further, the flows of continuum fluids are described by the local averaged Navier–Stokes equations that can be solved by CFD, with the coupling of fluid and solid phases being considered through the interactions between particles and fluid. It can, to a large extent, overcome the problems associated with the CFD–LPT model and has been increasingly used to study hydrocyclones in dense and/or dilute regimes by different investigators (Nowakowski et al., 2000; Huang, 2005; Brennan et al., 2007; Noroozi and Hashemabadi, 2009; Davailles et al., 2012; Kuang et al., 2012; Min'kov and Dueck, 2012; Narasimha et al., 2012; Swain and Mohanty, 2013). However, while confirming the capability of TFM approach, the previous studies have not covered the geometrical effects on hydrocyclone flow and performance.

In this study, hydrocyclones of different conical configurations have been studied in a wide range of feed solids concentrations using a recently developed TFM model (Kuang et al., 2012). This aims at gaining a better understanding of the effects of conical part on the flow and performance of hydrocyclones, and identifying possible methods to improve the cyclone performance. First, the effects of length and shape of conical section are studied. On this base, a new hydrocyclone design is proposed by replacing the conventional cone with a long convex cone. The results show that the new hydrocyclone has a better performance compared to the conventional cyclone at all the feed solids concentrations considered.

2. Simulation method and conditions

The present study is based on the TFM model which has been proved to be valid for hydrocyclones (Kuang et al., 2012; Ghodrat et al., 2013). In the model, both the fluid (liquid and air) and solid phases are treated as interpenetrating continua. Particles of different sizes or densities represent different phases. In this study, the density is considered constant, while the size is specified according to the size distribution given. To carry out a simulation, the size distribution is divided into a series of size intervals, with each represented by a mean size in the simulation. The flow of liquid–gas–solid mixture (as a single phase) is calculated from the continuity and the Navier–Stokes equations based on the local mean variables over a computational cell, considering slip velocities between different phases (Manninen et al., 1996). This gives the interface between the liquid and air core and the flows of liquid and particles of different sizes. The turbulent flow of the liquid–gas–solid mixture is modelled using the Reynolds stress model (Launder et al., 1975). The solid properties are described by the kinetic theory based on the algebraic temperature model (Syamlal et al., 1993). The applicability of the model has been verified by the good agreement between the measured and calculated results in terms of hydrocyclone flow and performance at different feed solids concentrations, as discussed elsewhere (Kuang et al., 2012). Here, the model is directly used to conduct numerical experiments to study the effects of different conical configurations.

The present operational and geometrical conditions, as listed in Table 1, follow Hsieh's experimental work (1988), whose measurements have been widely used in the literature to validate various numerical models including the present model. Two geometrical variables are considered here: length and shape of conical section. The conical section length L_{co} is varied from 35 mm to 385 mm at a fixed spigot diameter, selected according to the work of Wang and Yu (2006) for comparison, who studied the effect of conical section length in a dilute regime. Note that both dilute and dense regimes are considered for the two geometrical variables in this study by varying feed solids concentration *SC* from 4% to 30% by volume. The shapes include concave, straight (conventional design), and convex types. The function of $z = (r - D_c/2)^n/(D_u/2)$ is proposed to describe all the shapes, where z is the vertical distance of the conical surface away from the spigot bottom, r is the radial distance of the conical surface away from the central line of cyclone; D_c and D_u are the cylinder and spigot diameters, respectively; and n is referred to as the conical shape factor and varies between 0.3 and 3. By definition, the cone is concave at $n < 1$, convex at $n > 1$ and straight at $n = 1$ (see Fig. 1). All the cyclones considered have the same inlet, cylinder, and vortex finder as those of the base case. The same grid scheme as used and tested elsewhere (Wang and Yu, 2006, 2008, 2010; Kuang et al., 2012) is applied to all the cyclones considered, so that the solutions are independent of the mesh size used. A "velocity inlet" boundary condition is used at the cyclone inlet, and the "pressure-outlet" condition at both outlets. The inlet velocity is 2.49 m/s, and the pressure at the two outlets (vortex finder and spigot) is 1 atm, corresponding to the ambient atmospheric pressure. For particles, their (true) density

Table 1
Geometrical and operational conditions used in the simulations.

Parameter	Symbol	Value*
Geometrical parameters		
Diameter of the body	D_c	75 mm
Diameter of inlet	D_i	25 mm
Diameter of vortex finder	D_o	25 mm
Diameter of apex	D_u	12.5 mm
Length of cylindrical part	L_c	75 mm
Length of conical part	L_{co}	186 (35–385) mm
Length of vortex finder	L_v	50 mm
Cone angle	α	20°
Conical shape factor	n	1.4 (0.3–3)
Operational conditions		
Inlet velocity	u	2.49 m/s
Particle material		Limestone
Particle density	ρ_p	2700 kg/m^3
Feed solids concentration	*SC*	4.14 (4.14–30) % by volume
Particle sizes simulated	d	2.4–134 μm

* For the base case, with their varying ranges in the brackets.