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CFD STUDY OF THE MULTIPHASE FLOW IN CLASSIFYING HYDROCYCLONE: EFFECT OF CONE GEOMETRY

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ABSTRACT

This paper presents a numerical study of the gas–liquid–solid flow in hydrocyclones by a recently developed continuum-based multiphase flow model. The applicability of the model has been verified by a good agreement between the calculated and measured flow fields and separation efficiency (Kuang *et al*., 2012), and is used here to study the effect of cone length from a feed solids concentration of 4 to 30% (by volume). The numerical results show that for a standard design of cone section, decreasing cone length leads to the decrease of separation efficiency and the increase of inlet pressure drop for a given feed solids concentration. It is also shown that the performance of the cyclone with a short cone section is very sensitive to feed solids concentration.

KEYWORDS: Classifying hydrocyclone, Simulation, Cone geometry, Separation efficiency

INTRODUCTION

Classifying Hydrocyclones (CH) are widely used to separate particles by size in many industries such as chemical, mineral, coal preparation, and powder processing industries. Some advantages associated with this method of particle classification include design simplicity, high capacity, low maintenance and operational costs, and compactness. On the other hand, the disadvantages of CH include high energy loss and unsatisfactory separation efficiency with regard to missed particles in both the overflow and underflow due to simultaneous size- and density-based separations, and limitations on separation performance in terms of the sharpness of the cut and the range of operating cut size. To achieve efficient operation and optimum design of CH, it is essential to make the slurry flow field, especially that of the particles, as clear as possible.

The flow inside a CH is very complicated, because of the presence of swirling turbulence, air core and segregation, and involves multiple phases: liquid, gas, and particles of different sizes and densities. This causes difficulties in measuring detailed particle flow behaviours, in particular when the feed solids concentration involved is relatively high. In principle, numerical simulations can be used to overcome the problems associated with experimental measurement, and thus have been increasingly used to study CH (Narasimha *et al*., 2007). These studies have been mainly with low feed solids concentration due to the inherent deficiencies of the numerical models involved. However, the flows are not dilute in many practical applications, which affected significantly by feed solids concentration (Slechta and Firth, 1984 and O'Brien *et al*., 2000). Recently, Kuang *et al.* (2012) have developed a comprehensive computational fluid dynamics (CFD) model to describe CH flows and performances under a wide range of feed solids concentration.

It is well-recognized that CH geometry is a determinant factor affecting CH performance, with the cone section playing a critical role. Therefore, the dimensions and shape of cone section have attracted significant interest. For example, Svarovsky (1984) has experimentally observed that the cylindrical section may be short or even omitted, whereas the conical section is essential. Chiné and Concha (2000) have experimentally compared the conical and cylindrical CH, and found that the tangential velocities in both separator designs are similar while the axial velocities are different. Chu *et al.* (2002) have experimentally observed that the particle radial velocity is higher with a smaller cone opening or spigot diameter. A small spigot also leads to a rope discharge instead of spay discharge, increased cut size, and decreased water split (Saengchan *et al.* 2009), and should be restricted to a low feed solids concentration (Rietema, 1961). Wang *et al.* (2006) have numerically studied different cone lengths, suggesting the use of a long cone section if possible. Kilavuz and Gülsoy (2011) have experimentally reported that for a smaller CH, with increasing cone opening to vortex finder diameter ratio, the by-pass flow initially decreases sharply before becoming less sensitive. Based on physical and numerical experiments, Chu *et al.* (2002), Xu *et al.* (2009), and Yang *et al.* (2010) have observed that modification of a traditional design of cone section can lead to better performances of CH with respect to separation behaviour, capacity, wear, and energy consumption. However, most of the above studies were focused on low feed solids concentrations. To the best of our knowledge, a comprehensive study of cone geometry, including dimension and shape under different feed solids concentrations has not been reported in literature.

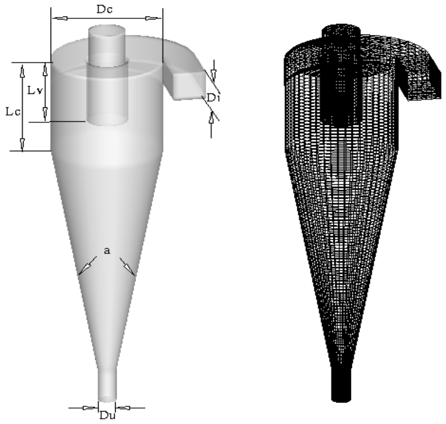
In this work, as the first step of our effort towards a comprehensive understanding of the effect of cone geometry on CH flow and performance, we studied traditional CH with different cone lengths from a feed solids concentration of 4 to 30% (by volume). The results show that the performance of CH may be sensitive to cone length, depending on the feed solids concentration involved.

MODEL DESCRIPTION

The present numerical method is a continuum-based model. In this model, particles are treated as continuous media, similar to the gas and liquid phases, and each particle size or density is represented by one solid phase. In the present work, the variation in particle density is negligible and thus not considered. The turbulent flow of liquid-gas-solid mixture is modelled using the Reynolds stress model. The interface between the liquid and air core, and the particle flow are both modelled using the mixture multiphase model. The mixture model is a simplified Eulerian model, considering the differences among particles, gas and liquid phases using Algebraic slip model (Manninen *et al*., 1996). The solid properties are described by the kinetic theory (Syamlal *et al.*, 1993). Such an approach can be applied to different feed solids concentrations, and thus overcome the deficiency of the Lagrangian particle tracking (LPT) method which is limited to dilute-phase flow (although it being currently the major numerical model used to study CH). The detail of the present model can be found elsewhere (Kuang *et al.*, 2012) and is not given here to avoid repetition.

SIMULATION CONDITIONS

Fig. 1 shows the computational domain meshed with hexahedral grid which contains 110,000 cells. In the vicinity of the walls and vortex finder, the grid is finer than the remainder of the cyclone. Trial numerical results were conducted to ensure that the mesh size was small enough to produce mesh-independent numerical solutions. Note that in the simulations, the circular cross section of an inlet is treated as square with the same area to improve numerical stability.



(a) (b)

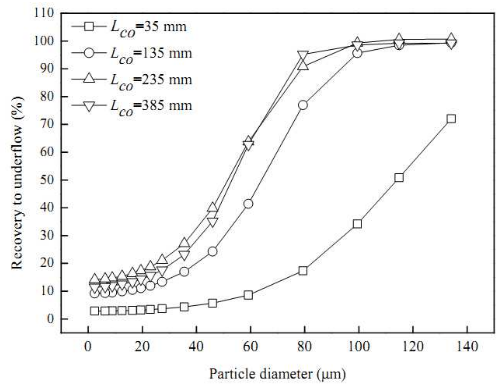
Figure 1 CH used for the classification of limestone: (a) geometry of the CH, and (b) mesh in the computation domain.

Table 1 lists the geometrical and operational parameters, determined based on the experimental work of Hsieh (1988). Such experimental conditions have been used to verify the applicability of the present model in terms of flow velocity, pressure drop, partition curve and water split (Kuang *et al.*, 2012). In this work, the variables considered include cone length and feed solids concentration. Eleven particle sizes varying from 2.4 to 134 micron as listed in Table 1 are simulated. Compared to the experimental conditions (the size range varying from 0.43 to 42.1 µm) (Hsieh, 1988), this study considered a much wider range of particle sizes, mainly with more coarse particles at the same size distribution as that given in the experiment (Hsieh, 1988). This allows us to use a relatively small computational effort to obtain more detailed behaviour of different sized particles under different conditions in particular for relatively coarse particles. Other simulation parameters used in this work are the same as those used in the experiment of Hsieh (1988). All the simulations here are conducted by the ANSYS Fluent CFD software package (version 12) in NCI (National Computational Infrastructure) HPC systems. Sixteen CPUs are assigned to each simulation, which lasts for about 14 days.

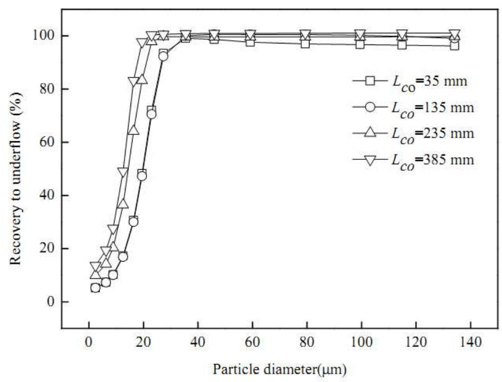
Table 1 Geometrical and operational conditions considered in the present work.

Parameter	Symbol	Value
Geometrical parameter		
Body diameter	D_c (mm)	75
Inlet diameter	D_i (mm)	25
Diameter of vortex finder	D_o (mm)	25
Spigot diameter	D_u (mm)	12.5
Length of cylindrical part	L_c (mm)	75
Cone length	L_{co} (mm)	35,135,235,385
Cone angle	α (°)	20
Operational Condition		
Inlet velocity	u (m/s)	2.49
Particle material		Limestone
Feed solids concentration (by volume)	SC (%)	4.14, 10, 20, 30
Particle density	ρ_p (kg/m^3)	2700
Particle sizes simulated	d (µm)	2.4~134

RESULTS



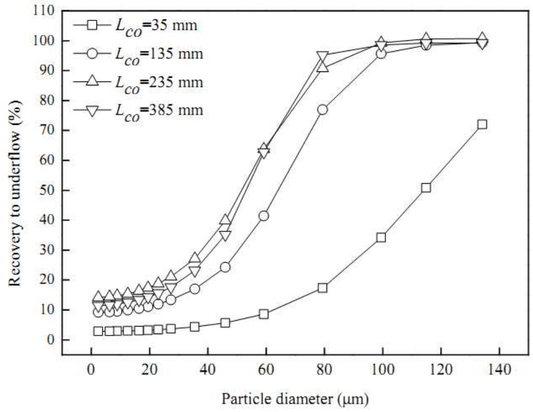
(a)



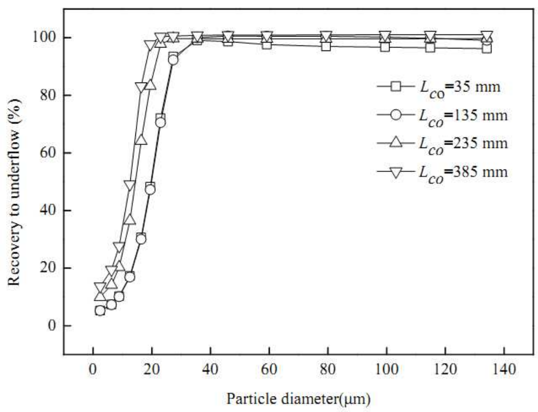
(b)

Figure 2 Effect of cone length on solid recovery to underflow at (a) SC=30%, and (b) SC=4.143%.

Figure 2 shows the effect of cone length on separation efficiency under the highest and the lowest feed solids concentrations (SC) considered in this work. It can be seen from the figure that for a given feed solids concentration, the separation efficiency increases with the increase of cone length. Moreover, the increase is smooth at a low feed solids concentration but not at a high feed solids concentration. Moreover, when feed solids concentration is high, for the CH with the shortest cone section, the coarsest particles do not completely report to the underflow as those in the CH with relatively long cone sections. In general, for the CH operated with a low feed solids concentration, the results obtained here are similar to those obtained by Wang *et al.* (2006) using the LPT model. This further confirms the result that the present model and LPT model largely match each other under conditions of low feed solids concentration (Kuang *et al.* 2012). Note that the LPT model cannot be applied to high feed solid concentration, although is it far more computational efficient compared to the mixture model. More details about the advantages and disadvantages of different models applied to CH can be found in the work of Kuang *et al*. (2012).



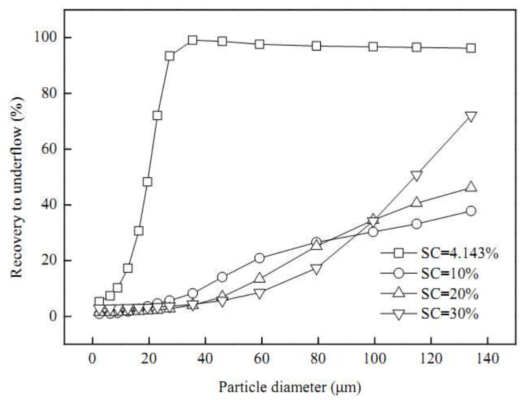
(a)



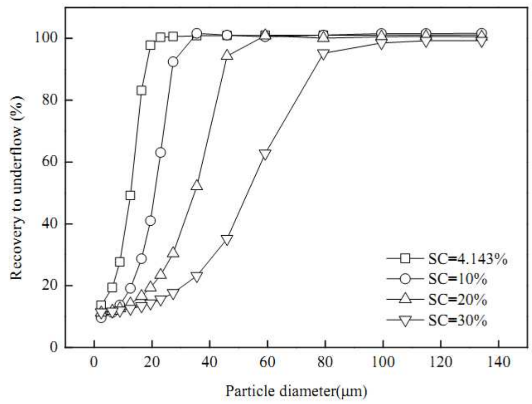
(b)

Figure 2 Effect of cone length on solid recovery to underflow at (a) SC=30%, and (b) SC=4.143%.

To better understand the effects of feed solids concentration in the CHs with different cone lengths, we examine the predicted partition curves under different feed solids concentrations for a given cone length, and the results are given in Figure 3. It can be seen from this figure that the separation efficiency nearly monotonously decreases with the increase of feed solids concentration when the cone length of CH is long enough, as observed experimentally by O'Brien *et al*. (2000). Conversely, when the cone length is too short, with increasing feed solids concentration, the separation efficiency initially drops drastically, and then gradually varies, featured with the decrease for the relatively small particles but the increase for the relatively coarse particles, as shown in Fig. 3a.



(a)



(b)

Figure 3 Effect of feed solids concentration on the solid recovery to underflow in a CH with (a) L_{co} =35 mm, and (b) L_{co} =385mm.

Figure 4 shows the typical spatial distributions of pressure drop inside the CHs with different cone lengths at two representative feed solids concentrations. It can be seen from the figure that for all the CHs considered, the pressure drop is the highest at the walls and decreases along the radial direction to the minimum at the center. Overall, shorter cone length or higher feed solids concentration leads to higher pressure drop.

Figure 5 quantitatively compares the inlet pressure drops, as indice of CH energy efficiency, for all the cases considered in this work. It can be seen from the figure that being consistent with the results in Figure 4, the inlet pressure drop decreases with the increase of cone length. The decrease is sharp when the cone length is short. However, when the feed solids concentration is increased, the inlet pressure drop increases sharply for the CHs with the shortest cone section, whereas decreases first to a minimum and then increases for the CHs with longer cone sections.

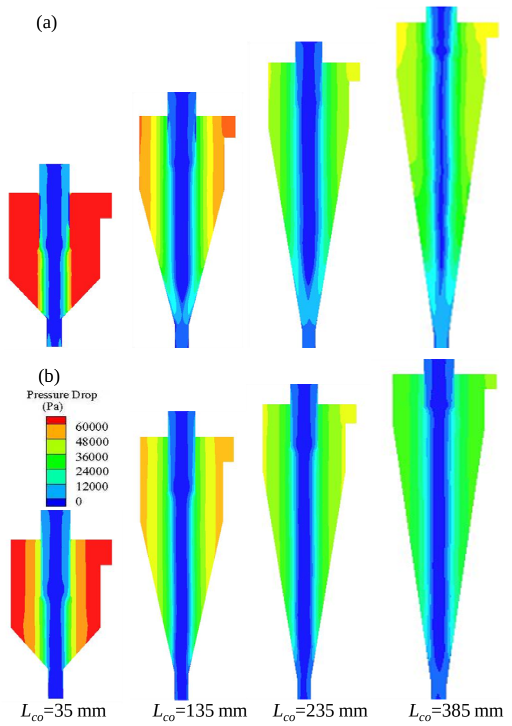


Figure 4 Spatial distributions of pressure in the CHs with different cone length at (a) SC=30% and (b) SC=4.143% at the plane *x*=0 m.

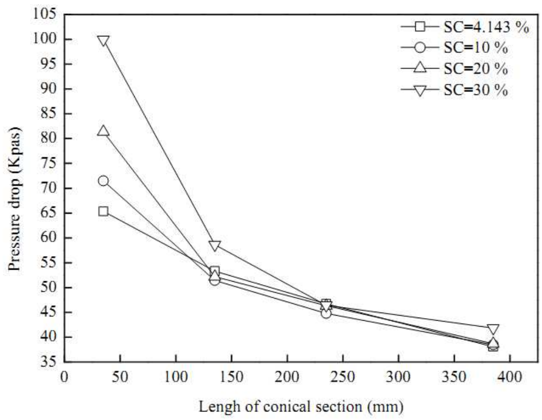


Figure 5 Inlet pressure drop as a function of cone length under different feed solids concentrations.

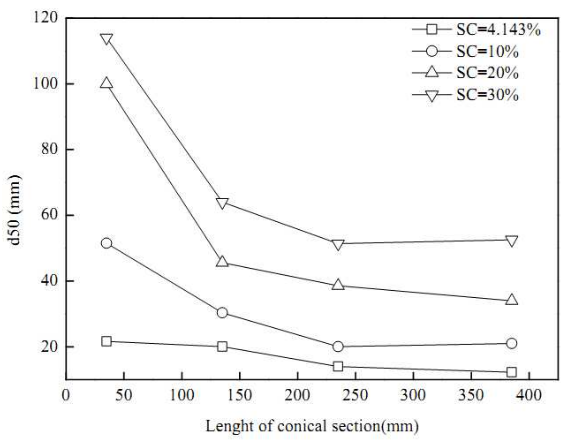


Figure 6 Cut size as a function of cone length under different feed solids concentration.

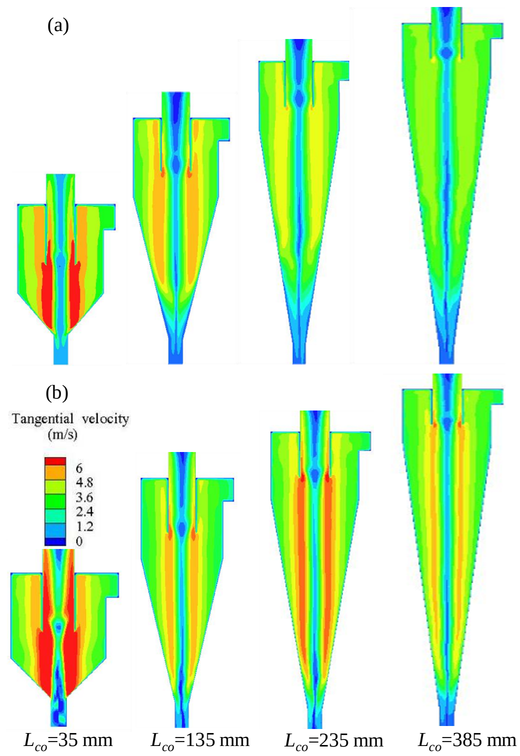


Figure 7: Spatial distributions of tangential velocities at (a) SC=30% and (b) SC=4.143% at the plane *x*=0 mm.

Figure 6 show the variations of cut size corresponding to the results in Figure 5. It can be seen from the figure that with increasing cone length, the cut size initially decreases sharply and then slows down. The increased feed solids concentration leads to the increase of cut size. Such effect is pronounced for the CHs with short cone sections.

Figure 7 plots the tangential velocities in the CHs with different cone lengths for two representative feed solids concentrations. It can be seen from the figure that for a given feed solids concentration, the tangential velocity decreases with the increase of cone length. Under such condition, the mixture density is not varied significantly due to the change of cone length, and the tangential velocity is responsible for the decreases in cut size and pressure drop. On the other hand, for a given cone length, the increased solid concentration leads to reduced tangential velocity and increased mixture density. Under such condition, the tangential velocity and mixture density together account for the behaviours of inlet pressure drop and cut size (Kuang *et al.*, 2012). How to quantify the collective effect is in progress.

Figure 8 shows how the water split is affected by the cone length under different feed solids concentrations. It can be seen from the figure that with the increasing cone length, the water split initially increases sharply and then slows down. The increased feed solids concentration leads to the increase of the water split. The effect is prominent when feed solids concentration is the highest.

CONCLUSION

Cone section plays a critical role for a CH to separate particles by size. The recently proposed CFD model has been used to study the flow and performance of CHs with different cone lengths under wide range of feed solids concentration. The results from the present work can be summarized as follows:

When cone length is increased under a given feed solids concentration, both the cut size and pressure drop initially decrease sharply and then slow down due to the increase of tangential velocity, whereas the water split initially increases sharply and then slows down.

When feed solids concentration is increased under a given cone length, as a result of the collective effect of increased mixture density and reduced tangential velocity, the inlet pressure drop increases sharply for the CHs with a short cone section, whereas decreases first to a minimum and then increases for the CHs with relatively long cone sections. The cut size and water split increase with the increase of solid concentration. The increase of cut size and water split are pronounced respectively for the CHs with short cone sections and for the highest feed solids concentration.

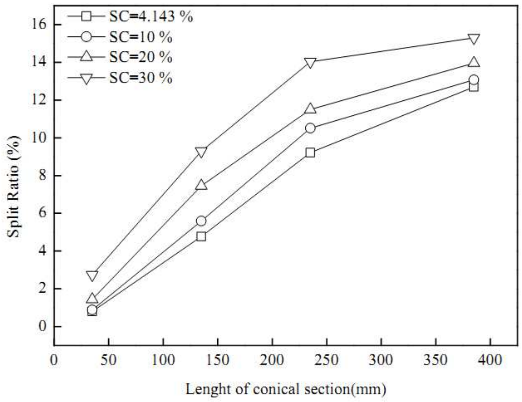


Figure 8 Water split as a function of cone length under different feed solids concentration.

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