Minerals Engineering xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Computational investigation of the effect of particle density on the multiphase flows and performance of hydrocyclone

M. Ghodrat [b], Z. Qi [a], S.B. Kuang [a,b,*], L. Ji [a], A.B. Yu [a]

[a] Laboratory for Simulation and Modeling of Particulate Systems, Department of Chemical Engineering, Monash University, Melbourne, VIC 3800, Australia
[b] Laboratory for Simulation and Modeling of Particulate Systems, School of Materials Science and Engineering, The University of New South Wales, Sydney, NSW 2052, Australia

ARTICLE INFO

Article history:
Received 17 August 2015
Revised 5 March 2016
Accepted 13 March 2016
Available online xxxx

Keywords:
Hydrocyclones
Multiphase flow
Separation
Particle density
Modelling and simulation
Coal preparation

ABSTRACT

Hydrocyclones are widely used to separate coal fines by size in the coal industry. They, however often face the problem associated with the misplacement of particles at the outlets due to the presence of a wide particle density range. This paper presents a numerical study of the multiphase flows and performance of hydrocyclone by means of two-fluid model, with special reference to particle density effect. The application of the model is firstly examined by comparing the measured and calculated results in terms of water velocities and particle partition curves. It is then used to investigate the behaviors of coal particles with different sizes and densities under different operational and geometrical conditions. The numerical results show that the separation efficiency of particles decreases with the decrease of particle density, and light coarse particles tend to be misplaced at the overflow outlet while ultrafine particles bypass the separation in proportion to the water split. These results are in line with the experimental observations. This misplacement problem is attributed to the significant accumulation of particles and weakened swirling flow in the spigot area. Based on these findings, the modifications on the standard hydrocyclone by either lengthening conical section or using a convex cone are proposed to improve the performance of cyclones used to handle different sized particles with a wide density range. The results show that both modifications are useful to reduce the amount of light coarse particles misplaced at the overflow outlet.

1. Introduction

Hydrocyclones are widely used in the coal industry to upgrade or separate coal fines smaller than 2 mm by particle size, due to their design simplicity, flexibility of operation, high capacity, and low operation and maintenance costs. However, two problems usually occur to this separation process. One is that ultrafine particles, either heavy or light, report to the underflow stream in proportion to the water split, thus by-pass the separation process, leading to the loss of the product that is light particles. Another is that light but coarse particles unexpectedly report to the overflow outlet. This situation results in negative impacts on the downstream operations like flotation, where the recovery of coal particles decreases when their size is too large (Firth et al., 1999; O'Brien et al., 2001). Some explicit approaches have been proposed in the past to overcome the first problem, for example, by means of adding dilution water to the feed, retreating the cyclone underflow through one or more extra cyclones in the same circuit, or injecting water into the cyclone from the location in the conical section (Firth et al., 1995, 1999; Honaker et al., 2001). However, at present the measures that target at solving the second problem are yet lacking. Furthermore, the two aforementioned problems are often geared to each other and thus more difficult to tackle. As such, the adverse effect of particle density has been a major issue associated with the application of hydrocyclone to the coal industry, especially for particles that are light and coarse (Firth et al., 1999; O'Brien et al., 2001). However, to date, the research efforts dedicated to the studies on the effect of particle density on the multiphase flows and performance of hydrocyclone are very few.

The flows in a hydrocyclone are very complicated because of the presence of swirling turbulence, air core, and segregation of coal particles, and involve multiple phases: air, water, particles of different sizes and densities. They govern unit performance but are difficult to measure, in particular when oblique coal slurry are involved in an industrial-scale hydrocyclone. Computer modelling and simulation can generate some insights into a hydrocyclone about the complicated multiphase flows and solid distributions,

* Corresponding author at: Laboratory for Simulation and Modeling of Particulate Systems, Department of Chemical Engineering, Monash University, Melbourne, VIC 3800, Australia.

E-mail address: shibo.kuang@monash.edu (S.B. Kuang).

http://dx.doi.org/10.1016/j.mineng.2016.03.017
0892-6875/

Nomenclature

a_k	acceleration of phase k (m/s^2)
d	particle size (m)
D	diameter (m)
$D_{T,ij}$	turbulence diffusion term
F_D	fluid drag force (N)
g	gravitational acceleration, 9.81 m/s^2
n	cone shape factor
N	number of phases
p	pressure drop (pa)
p_s	solid pressure (pa)
$P_{i,j}$	stress production term
SC	feed solids concentration
u	fluid velocity (m/s)
Re	Reynolds number

Greek letters

α	volume fraction
ε_{ij}	dissipation term
ρ	fluid density (kg/m^3)
τ	stress–strain tensor (kg/m/s^2)
$\gamma\Theta$	collisional dissipation of energy (J)
$\phi_{l,k}$	energy exchange between the lth solid phase and the kth solid phase (J)
ϕ_{ij}	pressure strain term
Θ	granular temperature (m^2/s^2)
μ	shear viscosity (kg/m/s)
λ	bulk viscosity (kg/m/s)

Subscripts

k	phase k
l	phase l
p	particle
s	solid phase

hence providing a better understanding of the separation behaviors of particles. In recent years, it has been extensively used to study hydrocyclones, in line with the development of computational technology, as reviewed by Nowakowski et al. (2004) and Narasimha et al. (2007). Generally speaking, the numerical models widely used can be classified into two groups: CFD-LPT (Computational Fluid Dynamics-Lagrangian Particle Tracking) and TFM (two-fluid model) approaches. The CFD-LPT approach traces only the motion of a single particle, and ignores the effect of inter-particle interactions as well as the reaction of particles on the fluid. Because of its computational efficiency, this approach has been used to study hydrocyclones under different geometrical and operational conditions but limited to dilute regimes or low feed solids concentrations due to the nature of CFD-LPT modelling (see, e.g., Hsieh and Rajamani, 1991; Wang and Yu, 2006; Bhaskar et al., 2007; Mousavian and Najafi, 2009b; Azadi et al., 2010). In the TFM approach, both the fluid and solid phases are treated as interpenetrating continuum media, considering the interactions between particles and between particles and fluid. It has been increasingly used to study hydrocyclones at different feed solids concentrations (Nowakowski et al., 2000; Huang, 2005; Cokljat et al., 2006; Brennan et al., 2007; Noroozi and Hashemabadi, 2009; Davailles et al., 2012; Kuang et al., 2012; Narasimha et al., 2012; Ghodrat et al., 2013; Swain and Mohanty, 2013; Ghodrat, 2014; Ghodrat et al., 2014a,b; Minkov et al., 2014; Safa and Soltani Goharrizi, 2014). Overall, almost all of the previous CFD-LPT and TFM studies of hydrocyclones neglected the particle density distribution in the feeds, likely because the effect of particle density is negligible under the specific conditions considered, e.g. the separation of limestone particles (Kuang et al., 2012; Ghodrat et al., 2013, 2014a,b). However, in the coal preparation the particle density range is wide and its effect on cyclone flows and performance may be significant, as discussed above. In addition, the feed solids concentration could be relatively high (O'Brien et al., 2001). Therefore, the TFM approach is needed in the modelling of hydrocyclones used in the coal industry, and has to consider the effects of both size and density of particles.

Generally, in the TFM approach, two different ways can be used to describe the flows of the phases within hydrocyclones. One applies a full set of conservative equations in regard with momentum and mass to each phase involved (Nowakowski et al., 2000; Davailles et al., 2012; Swain and Mohanty, 2013; Safa and Soltani Goharrizi, 2014). It is usually referred to as Eulerian–Eulerian model in the literature. Another is based on the so called mixture model which is a simplified Eulerian–Eulerian model and solves only one set of governing equations for all the phases, with an algebraic slip velocity model for each phase, so as to massively alleviate the computational loading of a full TFM model (Cokljat et al., 2006; Brennan et al., 2007; Noroozi and Hashemabadi, 2009; Kuang et al., 2012; Narasimha et al., 2012; Ghodrat et al., 2013; Ghodrat, 2014; Ghodrat et al., 2014a,b; Minkov et al., 2014). More recently, Kuang et al. (2014) and Qi et al. (2015) successfully applied a mixture model to simulate the behaviors of particles with different sizes and densities in dense medium cyclones (DMCs). Different from hydrocyclones, DMCs separate particles by density rather than size and generally consider much larger particles (50–0.5 mm), which are achieved mainly through adjusting the medium density by magnetite particles. On the other hand, the latest work of Ghodrat (2014) suggested that a mixture model is not accurate enough to model hydrocyclones used to handle different sized particles with a wide density range, though qualitative predictions are achievable. In that work, the results and analysis are largely preliminary because of the inaccuracy of the model.

The flows and performance of hydrocyclone are studied in this work by means of an Eulerian–Eulerian model, with special reference to particle density effect. The use of the Eulerian–Eulerian model aims to overcome the inaccuracy of the mixture model in describing the behaviors of different sized particles with a wide density range, in light of the fact that the former model is in principle more rational. The paper is organised as follows. First, the mathematical model is introduced, followed by the confirmation of model applicability by comparing the calculated results against the measurements in terms of water velocities for a water–air flow system, as well as particle separation efficiency for a water–air–solid flow system operated at low and relatively high feed solids concentrations. The flow characteristics of fluid and solid phases are then analyzed in details to better understand the effect of particle density. Finally, the modifications on hydrocyclone geometries to mitigate the adverse effect of particle density are discussed.

2. Simulation method

2.1. Model strategy

Because of the complexity of the flow in a hydrocyclone, the modelling is developed into three steps, as shown in Fig. 1. In step

Please cite this article in press as: Ghodrat, M., et al. Computational investigation of the effect of particle density on the multiphase flows and performance of hydrocyclone. Miner. Eng. (2016), http://dx.doi.org/10.1016/j.mineng.2016.03.017