Journal of the Taiwan Institute of Chemical Engineers 000 (2018) 1–7

Contents lists available at ScienceDirect

Journal of the Taiwan Institute of Chemical Engineers

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

Effects of particle mass loading on the hydrodynamics and separation efficiency of a cyclone separator

An-Ni Huang [a], Keiya Ito [b], Tomonori Fukasawa [b], Kunihiro Fukui [b,*], Hsiu-Po Kuo [a,c,**]

[a] Department of Chemical and Materials Engineering, Chang Gung University, Taoyuan 33302, Taiwan
[b] Department of Chemical Engineering, Graduate School of Engineering, Hiroshima University, Higashi-Hiroshima City, Hiroshima 739-8527, Japan
[c] Department of Otolaryngology-Head and Neck Surgery, Chang Gung Memorial Hospital-Linkou, Taoyuan 33305, Taiwan

ARTICLE INFO

Article history:
Received 30 September 2017
Revised 6 December 2017
Accepted 18 December 2017
Available online xxx

Keywords:
Cyclone
CFD
Particle mass loading
Separation efficiency

ABSTRACT

The effect of the particle mass loading (1.6–115.3 g/m^3) on the performances of a cyclone separator is studied by two-way coupling CFD simulation and experiments. The increasing of the particle mass loading enriches the particles at the wall region. At lower inlet air velocity, the separation efficiency increases with the increasing of the particle mass loading due to the larger particle sweeping effects and the aggregation of smaller particles. The full elastic particle–wall collision and the perfect dust box bottom collection assumptions cause CFD simulation overpredicting the separation efficiency of smaller particles. A partial elastic particle–wall collision assumption overcame the problem and reduced the calculated separation efficiency. Our CFD simulation can reasonably predict the separation efficiency at different particle mass loadings.

1. Introduction

Cyclones are common gas–solid inertia separators in industries because of their simple geometries, low cost in construction, maintaining and operations, and high flexibility to both mild and critical operating conditions. Typically, strong swirling flows are developed in a cyclone, causing the particles moving toward the cyclone walls and separating from the gas stream. Although the conceptual design of such a device is simple, the hydrodynamics of the gas and solids inside the cyclone separators is known to be complex [1–3]. Recently, the Computational Fluid Dynamics (CFD) based computer simulations have shown their abilities to understand the complex flow fields of the gas streams and the behavior of particles inside the cyclones of different designs [4,5]. Generally, these CFD studies could well predict the hydrodynamics of the pure gas streams in a cyclone separator using appropriate classical models. However, the presence of the particles complicates both the gas flows and solid motion and the computational predictions are more difficult.

The performances of the cyclones are usually evaluated based on the pressure drop across the cyclone and their separation efficiencies. The cyclone performances influenced by the gas temperatures and the inlet gas velocities have been widely studied [6,7]. However, the influences of the particle mass loading on the cyclone performances are less investigated. When the particle mass loading is greater than 500 g/m^3, the pressure drop across the cyclone decreases and gas tangential velocity weakens with the increasing of the particle mass loading [8–10]. Because of the sweeping effects of the larger particles and particle agglomeration inside the cyclone body, the cyclone separation efficiency increases with the increasing the particle mass loading [8]. When the particle mass loading is between 0 and 130 g/m^3, the cyclone separation efficiency also increases with the increasing the particle mass loading [11–14]. At relative lower particle mass loadings, Wan et al. showed that the gas tangential and axial velocities were similar to those corresponding values in the cyclone without adding particles when the particle mass loading was less than 30 g/m^3 [15].

It is challenging to well predict the hydrodynamics of the gas streams and the particle motion in a cyclone when gradually increasing the particle loading. Different methodologies have been adopted to study the hydrodynamics of the gas and solids in a cyclone. In a dilute particle-laden system, which has a particle volume fraction less than 10^{-5}, the interaction between the particles and the interaction between the particles and the gas stream are negligible and the one-way coupling simulation technique can be adopted [16,17]. When the particle volume fraction ranges from 10^{-5} to 10^{-3}, the interaction between the particles may be ignored. However, the influences of the particles on the surround-

* Corresponding author at: Department of Chemical Engineering, Hiroshima University, 1-4-1, Kagamiyama, Higashi-Hiroshima, 739-8527, Japan.
** Corresponding author at: Department of Chemical and Materials Engineering, Chang Gung University, 259 Wen-Hwa 1st Road, Taoyuan 33302, Taiwan.
E-mail addresses: kfukui@hiroshima-u.ac.jp (K. Fukui), hpkuo@mail.cgu.edu.tw (H.-P. Kuo).

https://doi.org/10.1016/j.jtice.2017.12.016
1876-1070/

Please cite this article as: A.-N. Huang et al., Effects of particle mass loading on the hydrodynamics and separation efficiency of a cyclone separator, Journal of the Taiwan Institute of Chemical Engineers (2018), https://doi.org/10.1016/j.jtice.2017.12.016

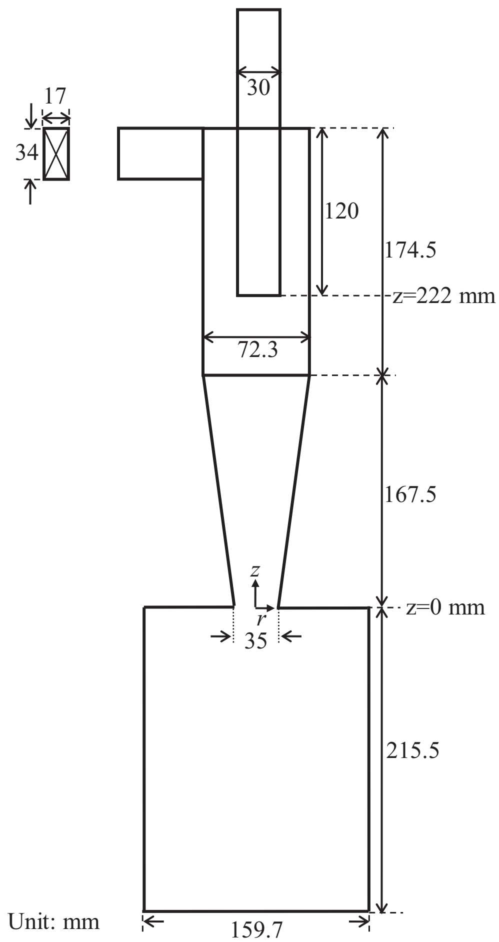

Fig. 1. The geometry and the main dimensions of the cyclone.

ing gas stream are typically considered using the two-way coupling simulation method [15,18]. In a denser particle-laden system with the particle volume fraction greater than 10^{-3}, the interactions between the particles, and the interaction between the particles and the gas streams should be taken cared. The sophisticated four-way coupling simulation technique has been utilized to study these systems [10].

Although the cyclone separation efficiency could be improved by increasing the particle mass loading [8,11–14], the roles of the particles at different particle mass loadings are still not clear. In this work, we study the effects of the particle mass loading, ranging from 1.6 g/m^3 (volume fraction = 5.52×10^{-7}) to 115.3 g/m^3 (volume fraction = 3.98×10^{-5}), on the hydrodynamics and separation efficiency of a cyclone separator using two-way coupling CFD simulations. Our simulation results were compared with the experimental data.

2. Experimental set-up

Fig. 1 shows the major geometric dimensions of the cyclone studied. The loading particles are Kanto loan powders (No. 11, JIZ 8901) with a density of 2900 kg/m^3. The size distribution of the powders was measured by a laser scattering particle sizer (LA-920, Horiba) using a 0.2 wt% sodium hexametaphosphate aqueous solution as the dispersant. The powders are in the range of 0.339–11.565 μm with a mean size of 2.1 μm.

In a typical experiment, the particles were fed into the system by a screw feeder and a dispersion device (VRL50, Nihon Pisco) using air as the dispersant. The tested particle loadings are listed in

Table 1
Particle mass loadings studied in this work.

		Particle mass flow rate (g/min)				
		1	3	15	30	60
Mass loading (g/m^3)	$V_g = 15$ m/s	1.9	5.8	28.8	57.7	115.3
	$V_g = 18$ m/s	1.6	4.8	24.0	48.1	96.1

V_g denotes the inlet air velocity.

Table 1. Ten different particle mass loadings were studied with the corresponding air velocities of 15 m/s and 18 m/s. Although the particle dispersion states might be slightly different at different particle mass loadings, we assume that the differences are minor and can be ignored due to there is no particle plugging found in the dispersion device even at high mass loadings. A glass fiber filter was fixed at the exit of the vortex finder to capture the escaping particles from the cyclone. The cyclone separation efficiency, $\Delta\eta$, was determined by

$$\Delta\eta(\%) = \frac{m_D f_D(\Delta D_p)}{m_D f_D(\Delta D_p) + m_V f_V(\Delta D_p)} \times 100\% \tag{1}$$

where m is the mass of the collected particles and $f(\Delta D_p)$ is the frequency of the particles in the size range of ΔD_p. The subscripts D and V represent the particles collected in the dust box and from the vortex finder, respectively.

3. Numerical simulation methods

The particle-laden gas flows in the cyclone were studied using the Eulerian–Lagrangian approach. The gas turbulent flows inside a cyclone were modeled by the Reynolds stress model (RSM), which has been shown being able to capture the flow characteristics [19,20]. The pressure-based Coupled algorithm [21] was used to solve the finite volume method based continuity and momentum governing equations. While the first-order upwind scheme was applied to discretize the Reynolds stress transport equation, the momentum, turbulent kinetic energy, and turbulent dissipation rate equations were discretized by the second-order upwind scheme. The PRESTO! scheme was used to interpolate the pressure at the grid faces.

Since the particle volume fraction is lower than 10^{-3} in most regions, the interaction between the particles was negligible and the two-way coupling method considering the interaction between the particles and the gas stream is used in our simulation work. The particle motion was determined by the Newton's second law as:

$$\frac{dv_p}{dt} = \frac{v_g - v_p}{\tau_r} + \frac{g_c(\rho_p - \rho_g)}{\rho_p} \tag{2}$$

where v is the velocity; ρ represents the density; g_c is the gravitational acceleration. The subscripts g and p represent the gas and the particles, respectively. τ_r in Eq. (2) considers the particle-gas drag by

$$\tau_r = \frac{\rho_p d_p^2}{18\mu} \times \frac{24}{C_D Re} \tag{3}$$

where d_p is the particle diameter; μ is the gas viscosity; C_D is the drag coefficient. Re is the relative Reynolds number, which is defined as

$$Re = \frac{\rho_g |v_p - v_g| d_p}{\mu} \tag{4}$$

Here, the Rosin–Rammler equation was used to account for the particle size distribution in the simulations. The particles are assumed as smooth particles and the drag coefficient, C_D, calculation follows that of Morsi and Alexander [22]. On top of considering the