Powder Technology 294 (2016) 437–448

Contents lists available at ScienceDirect

Powder Technology

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

Numerical analysis of forces exerted on particles in cyclone separators

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ARTICLE INFO

Article history:
Received 31 October 2015
Received in revised form 18 February 2016
Accepted 26 February 2016
Available online 4 March 2016

Keywords:
Cyclone separator
Centrifugal force
Drag force
Particle dynamics
Separations
Computational fluid dynamics

ABSTRACT

The motion of solid particles in a cyclone separator is studied using computational fluid dynamics (CFD). The Reynolds stress model (RSM) is used to simulate the turbulent flow of gas, and the outcome is used in the simulation of particle motion by adopting the stochastic Lagrangian particle tracking model (LPT). Additionally, the numerical results are compared with known experimental data to verify the applicability of the models. The results are analysed in terms of the particle velocity and of the force field that acts on the particles. It is shown that the particles are distributed from the wall toward the centre with decreasing particle size. The particle motion is mainly governed by the drag force and the centrifugal force; other forces, such as the pressure gradient force, Saffman lift force and added mass force, can be neglected. The inward drag force pushes the particles toward the centre and balances the outward centrifugal force on the particles in the radial direction. For large particles, the drag force is obviously less than the centrifugal force, and all of the particles are pushed to the wall and collected. As the particle size decreases, the drag force gradually increases, while the centrifugal force changes slightly. Thus, the difference between the drag force and the centrifugal force decreases and may be less than the changes that are caused by gas turbulence at some locations. The fate of the particles may be decided by the drag force variations that are caused by gas turbulence. When the size is below a critical value, the drag force increases abruptly and is significantly greater than the centrifugal force. Therefore, the motion of fine particles completely depends on the movement of gas.

1. Introduction

The cyclone separator, which is an important piece of gas–solid separation equipment, has been widely used in many industries because of its relative geometric simplicity, as well as its low manufacturing, operational and maintenance costs. Despite its superficial simplicity, the internal flow of a gas and particles in a cyclone is extremely complex. Currently, there is no clear separation theory that accurately describes the various factors that are involved in separation. It is known that the applied force on the particles is the decisive factor that governs the separation process of a particle. However, the mechanical behaviour of particles in cyclone separators is not completely understood.

In the early history of cyclone separation, researchers from different countries proposed several hypotheses for the separation mechanism of particles in cyclone separators after making various assumptions regarding the separation process. The residence time theory [1], the balanced orbital theory [2–4] and the boundary layer theory [5,6] are three representative hypotheses. The most widely adapted these theories is the balanced orbital theory, which is based on the force balance of a particle swirling on the interface between "inner" and "outer" vortices. The inward drag force that acts on the particle due to the motion of a gas moving from the outer to the inner vortex is proportional to the particle diameter in the Stokes regime, while the outward "centrifugal force" is proportional to the cube of the particle diameter. Large particles are thus separated, while small particles are dragged into the inner vortex and subsequently escape from the separator.

However, the above hypotheses do not explain the actual separation process since they are based on certain assumptions. Some scholars have tried to experimentally study complex two-phase flow. In early studies, only airflow was considered, and the corresponding flow fields were measured. In the work of Ter Linden [7], which is the most significant of these early studies, the three-dimensional flow field was measured using a spherical pitot tube, and the complexity of the flow was revealed for the first time. As technology developed, the flow field of air was measured using a laser Doppler anemometer (LDA) [8], which showed that the contraction of the spigot resulted in an increase in velocity fluctuations. This result is caused by a three-dimensional, unsteady-flow phenomenon called the precession vortex core (PVC) [9], which has a negative effect on the separation efficiency [10]. Because the fluctuations that are caused by the PVC are in the internal swirl area [11], the PVC phenomenon mainly affects the motion of small particles. Additionally, some other phenomena, including the

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http://dx.doi.org/10.1016/j.powtec.2016.02.052
0032-5910/

natural turning length and vortex core breakdown, also affect particle movement in a cyclone separator [12]. To study the influence that a gas within a cyclone has on the entrained particles, some scholars have measured the particle velocity. Solero and Coghe [10] measured the particle velocity using LDA and subsequently compared the gas velocity with the particle velocity. The result showed that the difference between the gas and particle velocities significantly affected the particle motion, indicating that the gas drag force plays an important role in controlling the particle motion. Su and Mao [13] measured the gas solid flow using a particle dynamic analyser (PDA) and reported that the strong swirling flow in the centre produced a centrifugal force that threw the particles into the outer, quasi-free vortex region, in which the particles were likely to be collected due to the weak swirling intensity. Chan et al. [14] studied the particle motion using positron-emission particle-tracking technology and discovered that the mean values of the tangential and radial velocities near the cylinder wall were 1.5–2 m/s and 0.9–1.3 m/s. Li et al. [15] further studied the particle velocity using a fibre optic detection method. In the study, the particle velocity in the near-wall region was varied from 0.5–2.5 m/s, and its average value was not sensitive to the operational parameters.

Although an experimental study can describe the flow patterns in a cyclone practically, the measurement of the particle velocity using current measurement technology is unsatisfactorily restricted to measurements that are taken at fixed local positions. Due to the rapid development of computer and computational fluid dynamics (CFD) techniques, the use of numerical simulations to predict the performance of cyclones has received a lot of attention [12]. CFD can accurately predict the turbulent behaviour of a gas flow [16]. After considerable numerical simulations, the Reynolds stress model is considered the most suitable available turbulence model to describe the fluid flow within a cyclone separator [17–21]. To better describe the effects of turbulence, many researchers have studied the particle motion to elucidate the separation mechanism. Derksen [22] reported that the competition between the centrifugal force and the dispersion that is caused by turbulence determined if the particles had a chance to reach the core region of the cyclone, in which the particles were more likely to be entrained in the stream moving toward the exit pipe. Although this conclusion was reached by observing the particle concentration distribution, the motor process was not described in the study. Ma et al. [23] and Souza et al. [24] both simulated the particle motion in cyclone separators, and their results demonstrated that turbulence caused the re-entrainment of particles that would otherwise be collected and, consequently, hindered the separation efficiency. Wang et al. [25] tested the trajectories of different sized particles and found that coarse particles mainly remained on the conical cyclone wall when their sizes exceeded a critical value. He explained this phenomenon by analysing three forces that acted on the particles in the conical part. Xue et al. [26] found that the entrainment of fine particles occurred at a height 0.5 D above the dust discharge port and that a “shortcut flow” was present approximately 0.25 D below the entrance of the vortex finder. Wang and Yu [27] found that a short circuit flow existed along the outer wall of the vortex finder, resulting in a decrease in the separation efficiency, and that a thin vortex finder is helpful for a high separation efficiency, particularly for coarse particles. Additionally, Li et al. [28] indicated that the Saffman lift force accelerated the separation process and shortened the residence time of small particles. Cui et al. [29] concluded that the radial distribution of the particles was non-uniform due to the effects of the centrifugal force.

To date, most studies on the particle separation mechanism in cyclone separators have mainly focused on the kinematic vision in terms of the flow field of the fluid and the particles, and few studies have mentioned the dynamic behaviour of the particles in cyclone separators. This paper presents an analysis of the forces on particles in a cyclone, combining the flow field with the particle motion and the separation efficiency, to study the particle separation mechanism in depth and to provide a basic theory to optimise the design of cyclones.

2. Model description

2.1. Numerical modelling process

Considering the complexity of the gas-solid flow in a cyclone separator, the modelling process is divided into three steps, as shown in Fig. 1. In Step 1, only air is considered. The turbulent flow is modelled using the Reynolds stress model (RSM). In Step 2, different sized limestone particles are injected, and the number of injected particles is 11,200 for each size. The particle motions are traced using the stochastic Lagrangian particle tracking model (LPT). The separation efficiency of each particle size is the ratio between the tracked and injected particles, and the separation efficiency curve is obtained. In Step 3, the force information for five typical particle sizes is studied by applying User-Defined Functions (UDF) to further reveal the separation mechanism of particles in a cyclone separator.

The details of the RSM and LPT are briefly described below.

2.2. Reynolds stress model

The governing equations for an incompressible fluid can be written as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right). \tag{2}$$

The velocity components are decomposed into the mean $\overline{u}_i$ and fluctuating u_i' $(i=1,2,3)$ components, which are related by:

$$u_i = \overline{u_i} + u_i' \tag{3}$$

where the Reynolds stress term $-\rho\overline{u_i' u_j'}$ includes the turbulence closure, which must be modelled to solve Eq. (2).

The transport equations for the Reynolds stress term $-\rho\overline{u_i' u_j'}$ in the RSM are:

$$\frac{\partial}{\partial t}\left(\rho\overline{u_i' u_j'}\right) + \frac{\partial}{\partial x_k}\left(\rho u_k \overline{u_i' u_j'}\right) = D_{T,ij} + P_{ij} + \phi_{ij} + \varepsilon_{ij} \tag{4}$$

where the two terms on the left are the local time derivative of the stress and the convective transport term, respectively. The four terms on the right are:

The turbulent diffusion term: $D_{T,ij} = -\frac{\partial}{\partial x_k}\left[\rho\overline{u_i' u_j' u_k'} + \overline{p(\delta_{kj} u_i' + \delta_{ik} u_j')}\right]$.

The stress production term: $P_{ij} = -\rho\left(\overline{u_i' u_k'}\frac{\partial u_j}{\partial x_k} + \overline{u_j' u_k'}\frac{\partial u_i}{\partial x_k}\right)$.

The pressure strain term: $\phi_{ij} = \overline{p\left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}\right)}$.

The dissipation term: $\varepsilon_{ij} = -2\mu\overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_i'}{\partial x_k}}$.

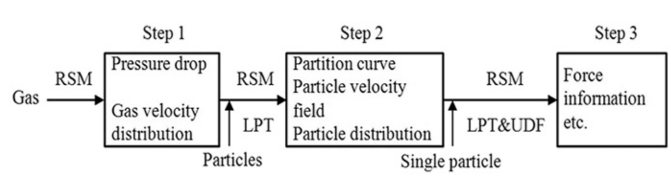

Fig. 1. Modelling process that was used in this work.