Powder Technology 250 (2013) 52–62

Contents lists available at ScienceDirect

Powder Technology

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

Experimental and CFD study of the hydrodynamic behavior in a rotating drum

D.A. Santos, I.J. Petri, C.R. Duarte, M.A.S. Barrozo *

School of Chemical Engineering, Federal University of Uberlândia, Bloco K, Campus Santa Mônica, 38400–902, Uberlândia, MG, Brazil

ARTICLE INFO

Article history:
Received 14 May 2013
Received in revised form 19 September 2013
Accepted 2 October 2013
Available online 10 October 2013

Keywords:
Flow regimes
Particle velocity
Granular viscosity
Frictional model

ABSTRACT

In this work the particle dynamic behavior in a rotating drum under different operating conditions has been analyzed based on experimental results and simulations. The Eulerian–Eulerian multiphase model with the kinetic theory of granular flow was used in the simulations. In order to evaluate the simulation results, different solid flow regimes and velocity distributions of the particulate phase were compared with experimental data. The experimental particle velocity distribution was obtained by using a high-speed video camera technique. The numerical simulation has contributed to understanding the main particle dynamics phenomenon present in rotating drums.

1. Introduction

Rotating drums are used in many industrial processes as mixers, dryers, granulators and reactors for processing granular materials. As a result, granular behaviour in rotating drums has attracted numerous research efforts from both engineering and physics communities over the past few decades [1–5]. However, the mechanisms of solids movement in rotating drums are still not completely understood. Knowledge of the solids flow pattern in rotating drums is essential to their design, because the particles' trajectories must meet process requirements.

Mellman [6] presents an overview of the forms and transition behavior of the transverse motion of bed materials in rotating drums. Different regimes of solids motion in a rotating drum have been identified as the rotational speed increases: sliding, surging, slumping, rolling, cascading, cataracting and centrifuging.

In the rolling mode, bed material can be divided into two distinct regions: passive and active. In the passive layer the particles are carried upward by the drum wall like a rigid body whereas in the active layer particles flow down the sloping upper bed surface. So, the entire mixing mechanism takes place in the active layer [7].

Many experimental studies have been conducted on rotating drums [8–11]. However, most of these studies have investigated drums operated only in or close to the rolling mode, which is not enough to validate mathematical models. Among many other variables, the measurement of particle velocity distribution at mid-chord of the bed material surface in the rotating drum is of fundamental importance to determine the magnitude of the active layer.

Ding et al. [12] employed the positron emission particle tracking (PEPT) to follow particle trajectory and velocity. However, according to Huang et al. [13], these experimental methods are limited in the size of observation, and applicable only for radioactive powders, not readily for ordinary granular flow studies.

Boateng and Barr [4] used optical fiber probes to measure mean particle velocities both within the bed and at the bed surface. Since this is an intrusive technique, it causes perturbations and consequent large measurement errors.

Based on the work developed by Duarte et al. [14] in spouted beds, the present authors suggest the use of a non-intrusive technique, which is composed by a high-speed video camera, in order to measure particle velocity in a rotating drum.

Nowadays, with the great development of the computational area, as regards the improvement of data processing and storage, the CFD (Computational Fluid Dynamics) technique has become a very useful tool in order to obtain detailed information about flow phenomena. Studies of numerical simulation by CFD technique have become popular in the field of gas–solid flow, in several applications [15–19]. Otherwise, this great technological advantage contrasts with the scarce of experimental data, which are of fundamental importance to validate mathematical models [20].

The two approaches commonly used in the simulation of particle dynamics in rotating drums are the Euler–Euler and Lagrange. In the Lagrange approach or Discrete Element Method (DEM), the forces acting on every particle in the system are calculated based on certain particle–particle interaction laws. On the other side, the DEM has a fatal problem, that is, the number of calculated particles is restricted due to the excessive calculation cost.

Yang et al. [21] investigated the granular flow dynamics in different regimes using the discrete element method. By varying the rotation

* Corresponding author. Fax: +55 34 32394188.
E-mail address: masbarrozo@ufu.br (M.A.S. Barrozo).

0032-5910/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.powtec.2013.10.003

speed and particle–wall sliding friction over a wide range, six flow regimes were produced. The macroscopic and microscopic behaviour of the particle flow were systematically analyzed. Many other researchers have adopted this kind of approach in the simulations of rotating drums [22–31].

In the Euler–Euler approach, the different phases are treated mathematically as interpenetrating continua. Since the volume of a phase cannot be occupied by the other phases, the concept of phasic volume fraction is introduced. These volume fractions are assumed to be continuous functions of space and time and their sum is equal to one.

Few reports have dealt with the fluid dynamic study of rotating drums using an Eulerian multiphase model [13,32,33]. Although DEM simulations provide microscopic information at particle level, Euler–Euler simulations require less computational time and are preferred for large scale granular flow modeling [13].

The prediction of the solids flow pattern in rotating drums is of primary importance to their design and applicability. So, the present work embodies an experimental campaign which was mounted for the purpose of obtaining direct measurement of the main variable related to granular flows, i.e. the particle velocity, by means of a non intrusive technique (high speed video camera), in rotating drums. The primary object was to provide guidance in the selection of constitutive relations which might enable granular flow modeling for rotating drums using the Eulerian approach.

2. Experimental setup

The experimental apparatus used in this work was composed by a drum and the associated driving and controlling unit. The cylindrical part was constructed with acrylic, while the two end plates were made from transparent glass to ease the flow pattern observations. Since the two end plates of the drum were made of transparent glass, which has low friction coefficient, the friction effect on the particle dynamics near the ends of the drum can be considerer of minor importance. So, as observed experimentally under the conditions investigated in the present work, the velocities observed at one end of the drum can be considered, approximately, the same as that at the middle of the drum. The drum was 19.5 cm in inner diameter and 50 cm in length. The inside wall of the drum was coated with a layer of rough material to prevent slippage between the bed material and the drum wall (no-slip condition). Rotation speed of the drum was measured by non-contact laser tachometer. A frequency inverter was used to control the motor speed.

Particles for the current study were glass beads of 1.09 mm and 3.68 mm in mean diameters and a density of 2460 kg/m^3. For these particles the loosely packed voidage was found to be 0.37. The fill levels of 18.81% and 31.40% were used for each particle diameter. The drum rotational speed was set at 1.45 rad/s, 4.08 rad/s, 8.91 rad/s and 16.4 rad/s to allow generation of four different regimes of solids motion: rolling, cascading, cataracting and centrifuging.

In order to measure the particle velocity, images of the transverse plane of the material bed were recorded using a high-speed video camera (maximum speed of 2000 frames per second). After recording, particle paths were observed and their velocity measured by the distance traveled and the respective number of frames. This procedure was used at mid-chord of the bed material surface in the rotating drum operated in the rolling regime with fill level of 18.81% and drum rotational speeds of 1.45 rad/s, 2.31 rad/s and 3.14 rad/s.

3. CFD simulations

3.1. Description of the model

A multiphase flow arises when the average motion of one material is essentially different from that of another. Thus, to model a multiphase flow, it's necessary to take into account the properties' conservations as well as the interaction between the involved phases. In the present investigation, the Eulerian multiphase model is used to model the flow in a rotating drum.

3.1.1. Conservation equations of mass and momentum and drag models

The mass conservation equation for fluid and solid phases is represented by the following equations:

$$\frac{\partial}{\partial t}\left(\alpha_f\right) + \nabla.\left(\alpha_f \vec{v}_f\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_s) + \nabla.(\alpha_s \vec{v}_s) = 0 \tag{2}$$

where $\vec{v}_f$ and $\vec{v}_s$ are the velocities of the gas and solid phases. The gas volume V_f, is defined by

$$V_f = \int_V \alpha_f dV \tag{3}$$

The conservation of the gas and solids momentum is given by the following equations:

$$\frac{\partial}{\partial t}\left(\alpha_f \rho_f \vec{v}_f\right) + \nabla.\left(\alpha_f \rho_f \vec{v}_f \vec{v}_f\right) = -\alpha_f \nabla p + \nabla.\overline{\overline{\tau}}_f + \alpha_f \rho_f \vec{g} + \alpha_f \rho_f \left(\vec{F}_{q,f} + \vec{F}_{lift,f} + \vec{F}_{vm,f}\right) + \left(K_{fs}\left(\vec{v}_f - \vec{v}_s\right)\right) \tag{4}$$

$$\frac{\partial}{\partial t}(\alpha_s \rho_s \vec{v}_s) + \nabla.(\alpha_s \rho_s \vec{v}_s \vec{v}_s) = -\alpha_s \nabla p - \nabla p_s + \nabla.\overline{\overline{\tau}}_s + \alpha_s \rho_s \vec{g} + \alpha_s \rho_s \left(\vec{F}_q + \vec{F}_{lift,s} + \vec{F}_{vm,s}\right) + K_{fs}\left(\vec{v}_f - \vec{v}_s\right) \tag{5}$$

where $\vec{F}_q$, $\vec{F}_{lift}$ and $\vec{F}_{vm}$ are an external body force, a lift force and a virtual mass force, respectively. In this investigation, only drag and gravity are considered with the lift force and virtual mass force neglected.

In order to couple the momentum transfer between gas and particle phases, a model for the drag force is required. This drag force is represented by the momentum exchange coefficient between the phases considered.

The momentum exchange coefficient (K_{sf}) between solid phase s and fluid phase f can be written in the following general form:

$$K_{sf} = \frac{\alpha_s \rho_s f_d}{\tau_s} \tag{6}$$

where f_d is the drag function and τ_s is the "particulate relaxation time" defined as:

$$\tau_s = \frac{\rho_s d_s^2}{18\mu_f} \tag{7}$$

where d_s is the diameter of particles in the solid phase (s) and μ_f is the fluid viscosity.

The definition of f_d includes a drag coefficient (C_D) that is based on the relative Reynolds number (Re_r), defined as:

$$\mathrm{Re}_r = \frac{\rho_f \left|\vec{v}_f - \vec{v}_s\right| d_s}{\mu_f} \tag{8}$$

In this paper, the momentum exchange coefficient is calculated following the model of Gidaspow et al. [34], which is a combination of the Wen and Yu [35] model and the Ergun equation [36].

The solids–fluid exchange coefficient K_{sf} takes the following form:for $\alpha_f > 0.8$:

$$K_{sf} = \frac{3}{4} C_D \frac{\alpha_s \alpha_f \rho_f \left|\vec{v}_s - \vec{v}_f\right|}{d_s} \alpha_f^{-2.65} \tag{9}$$