CHEMICAL ENGINEERING RESEARCH AND DESIGN 94 (2015) 204–212

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

A hydrodynamic analysis of a rotating drum operating in the rolling regime

D.A. Santos, F.O. Dadalto, R. Scatena, 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

ABSTRACT

An experimental and numerical investigation of the hydrodynamic behavior in a rotating drum, operated in the rolling regime, was performed in the present work. For all the simulations, the Euler–Euler approach was used. A high-speed video camera technique was used in order to measure, experimentally, the particle velocity distribution. The CFD simulations showed good agreement with the experimental results. The influence of different drag models on particle velocity profile was analyzed. It was observed that, the drag force can be neglected in the case of a rotating drum operated in the rolling regime where there is no fluid entering or leaving the system. From the experimental and simulated results it was possible to verify the effect of the rotation speed and filling degree on the particle velocity in the active region and on its thickness.

Keywords: Fluid dynamic; Rotating drum; Rolling regime; Active region; Passive region; Drag model

1. Introduction

Many industrial processes such as mineral, food processing, polymer production, ceramic manufacturing, metallurgical, pharmaceutical and biochemical processing, require large contact area between phases, which enhances heat and mass transfer. In this way, rotating drums arise as suitable equipments for processing granular materials in applications such as mixing, granulation, milling, coating and drying (Degrève et al., 2006; Dubé et al., 2013; Jin et al., 2012; Rocha et al., 2013).

The widespread use of rotary drums is also due to their ability to deal with large particle size distribution and significant difference in physical properties. However, the efficiency of rotating drums is highly dependent of fluid dynamics behavior.

The knowledge about this behavior is essential for scaling, design and optimization. Although these devices are simple and can be operated relatively easily, the granular dynamic behavior is quite complex (Chou and Hsiau, 2012).

Rotating drums can show seven different flow regimes (sliding, surging, slumping, rolling, cascading, cataracting and centrifuging), which depend on the rotational speed, filling degree, physical properties of granular materials and drum geometry (Mellmann, 2001). Each one with its own specific flow behavior, which increase the complexity in its study.

Due to rotating drums characteristics previously presented, many research works have been carried out in order to study: the flow regimes (Mellmann, 2001; Watanabe, 1999; Rajchenbach, 1990; Chou and Hsiau, 2012), the solids segregation behaviors (Lee et al., 2013; Huang and Kuo, 2012; Chou et al., 2010; Ding et al., 2002; Huang and Kuo, 2011), and the dynamics of particles (Santos et al., 2013; Dubé et al., 2013; Santomaso et al., 2003; Ding et al., 2001; Boateng and Barr, 1997).

The rolling regime is the most commonly operated flow regime in industry. This regime is characterized by two different regions: a passive region, found near the drum wall, where particles move as a solid body, and an active region, found near the bed material surface, where the particles avalanche and cascade downward. The physical mechanisms such as, mixing and segregation, heat and mass transfer, and so on, mainly occur in the active region (Dubé et al., 2013; Ding et al., 2001).

A reverse of the flow takes place at the active–passive interface (velocity inflexion point) as a result of the drum wall movement. The distance between the active–passive interface and the bed material surface characterizes the active region thickness. So, the particle velocity distribution knowledge is of fundamental importance to an accurate representation of the dynamics of the flow in rotating drums. For the particle velocity measurement there are different non-intrusive and intrusive techniques.

* Corresponding author. Tel. +55 34 96776099; fax: +55 34 32394188.
E-mail addresses: masbarrozo@ufu.br, masbarrozo@pesquisador.cnpq.br (M.A.S. Barrozo).

Available online 8 August 2014
http://dx.doi.org/10.1016/j.cherd.2014.07.028
0263-8762/

Nomenclature

C_D	drag coefficient [–]
d_s	particle diameter [m]
e_{ss}	restitution coefficient [–]
$\vec{g}$	gravity acceleration vector [m s^{-2}]
$g_{0,SS}$	radial distribution function [–]
k_{eS}	energy diffusion coefficient
K_{sf}	coefficient of momentum exchange between fluid phase *f* and solid phase *s*
$K_{sf\_Wen\_Yu}$	coefficient of momentum exchange from Wen and Yu (1966) model
K_{sf_Ergun}	coefficient of momentum exchange from Ergun (1952) model
p_S	solids pressure [Pa]
r	radial position [m]
Re_r	relative Reynolds number [–]
R	radius of the drum [m]
t	time [s]
V	volume [m^3]
$\vec{v}_f$	fluid velocity vector [m s^{-1}]
Vp	particle velocity [m s^{-1}]
$\vec{v}_s$	solid velocity vector [m s^{-1}]
F_r	Froude number [–]
p	pressure shared by all phases (fluid and solid) [Pa]

Greek symbols

α_f	fluid volume fraction [–]
α_S	solid volume fraction [–]
$\alpha_{S,max}$	maximum packing limit [–]
$\gamma_{\theta S}$	collisional dissipation of energy
θ_s	granular temperature [–]
λ_s	solid bulk viscosity
μ_f	fluid dynamic viscosity [cP]
μ_s	granular solid viscosity [cP]
ρ_f	fluid density [kg m^{-3}]
ρ_s	solid density [kg m^{-3}]
$\bar{\bar{\tau}}_f$	fluid stress tensor [Pa]
$\bar{\bar{\tau}}_S$	solid stress tensor [Pa]
ϕ_{fs}	energy exchange between gas and solid phase
ψ	switch function from Huilin et al. (2003) drag model
ω	rotational speed [s^{-1}]

Non-intrusive technique, which use γ-ray detectors in order to follow the motion of particles and consequently to determine their velocities. This technique has been used, among other researches, by Ding et al. (2002) and Dubé et al. (2013). However, these experimental methods are applicable only for radioactive particles. Another intrusive technique, based on Magnetic Resonance Imaging, was used by Nakagawa et al. (1993) and Yada et al. (2010).

Boateng and Barr (1997) used an intrusive technique, composed by optical fiber probes, to measure flow properties in a rotating drum. However, this technique can cause, depending on the probe geometry, perturbations and consequent large measurement errors.

Some works have demonstrated the feasibility of studying granular flows by using a high-speed video camera as a non-intrusive technique (Santos et al., 2013; Duarte et al., 2005). After recording, particle paths are observed and their velocity measured by the distance traveled and the respective number of frames.

Parallel to experimental studies, the numerical simulations arise as a complementary tool in the granular flows investigation. The Euler–Euler approach and the discrete element method (DEM) are the two methods frequently used in the simulation of granular flows.

In DEM method, all the particles are followed and the interaction forces acting on every particle are calculated. Although many researchers have adopted this kind of method in the simulations of rotating drums (Marigo et al., 2012; Xu et al., 2010; Liu et al., 2013; Chand et al., 2012; Jiang et al., 2011; Wachs et al., 2012; Finnie et al., 2005; Kwapinska et al., 2006), there is restriction on the number of particles present in the equipment due to computational cost.

On the other hand, in the Euler–Euler approach, both phases are treated as interpenetrating continua and solved on an Eulerian frame of reference. Numerical simulation studies by using Euler–Euler approach have become popular in the field of gas-solid flow, in several applications (Santos et al., 2009, 2012a, 2012b, 2013; Cunha et al., 2009; Barrozo et al., 2010; Oliveira et al., 2009; Duarte et al., 2009).

There are restricted number of works related to the fluid dynamic study of the rotating drums using the Euler–Euler approach (Huang et al., 2013; He et al., 2007; Demagh et al., 2012; Santos et al., 2013; Yin et al., 2014), most of them used in segregation studies, and all of them have used the Gidaspow et al. (1992) drag model to estimate the drag force.

Although some parameters related to the material properties and scale of the rotating drum have been investigated, the influence of the drag force on the flow characteristics has not yet been examined. Thus, in this study, the particle dynamics in a rotating drum operated in the rolling regime has been investigated by both experimental tests and numerical simulations. The Euler–Euler approach and the kinetic theory of granular flow were used in the simulations. The influence of different drag models on particle velocity prediction was also investigated.

2. Materials and methods

2.1. *Experimental setup*

The cylindrical column of the drum was made of stainless steel and the two end walls were made of glass to allow the flow pattern observation. The drum was 21.5 cm in inner diameter and 50 cm in length. A sandpaper (P80) was used to coat the inside wall of the drum in order to prevent slippage between particles and drum wall (no-slip condition). The particle used in the present work was soybean of 6.2 mm in diameter and density of 1164 kg/m^3. For this particle the loosely packed voidage was found to be 0.4.

The velocity distributions of particles at the mid-chord of the bed material surface (reference line in Fig. 1), under

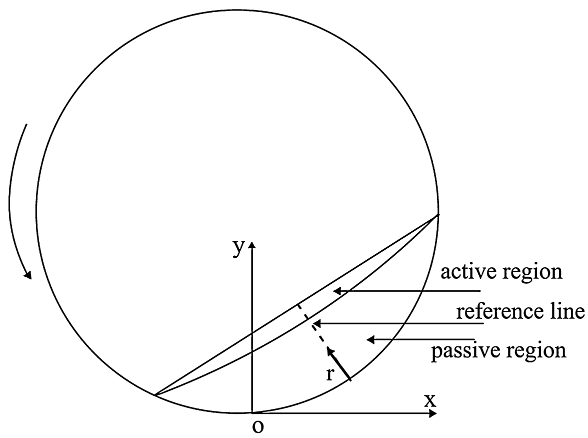

Fig. 1 – Transverse plane of the rotating drum operated in a rolling regime showing the coordinate system used for particle velocity measurement and the active and passive regions.