Powder Technology 251 (2014) 15–24

Contents lists available at ScienceDirect

Powder Technology

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

Numerical study of horizontal pneumatic conveying: Effect of material properties

K. Li [a], S.B. Kuang [a], R.H. Pan [b], A.B. Yu [a,]*

[a] Laboratory for Simulation and Modelling of Particulate Systems, School of Materials Science and Engineering, The University of New South Wales, Sydney, NSW 2052, Australia
[b] Longking Bulk Materials Science and Engineering Co., Xiamen 361000, China

ARTICLE INFO

Article history:
Received 2 February 2013
Received in revised form 2 September 2013
Accepted 11 October 2013
Available online 22 October 2013

Keywords:
Discrete element method
Pneumatic conveying
Friction coefficient
Restitution coefficient
Flow transition

ABSTRACT

This paper presents a numerical study of the effects of friction and restitution coefficients of particles on horizontal pneumatic conveying by a combined approach of computational fluid dynamics for gas and discrete element method for particles. The flow behaviours are analysed in terms of particle flow pattern, gas pressure drop, solid concentration, particle velocity and transition of flow regime. The results show that in the slug flow regime, an increased friction coefficient or a decreased restitution coefficient results in longer slugs but no change in slug shape. Slug flow cannot be obtained at a low friction coefficient. In the stratified and dispersed flow regimes, the transition between the two regimes and formation of clusters occur due to the changes of friction and/or restitution coefficient. These two coefficients also affect the pressure drop, particle velocity and solid concentration. The resulting effects vary with flow regime. Overall, the effect of restitution coefficient is less significant than that of friction coefficient. It is also found that when gas velocity is varied from high to low values, three flow transition modes may occur depending on friction and restitution coefficients. They are respectively represented by Mode I for dilute-phase only, Mode II for unsmooth transition from dilute-phase to unstable-zone, and finally to slug-flow, and Mode III for smooth transition from dilute-phase to slug-flow. Based on the numerical results, a diagram is established to predict these transition modes as a function of friction and restitution coefficients.

1. Introduction

Pneumatic conveying is a method for transport of bulk materials in many industries. Its flow and performance depend on pipe geometries, operational conditions and particle properties [1]. Generally speaking, particle properties can be classified into two groups: particle characteristics (e.g. size, size distribution, and shape) and material properties (e.g., density, hardness, Poisson's ratio, Young's modulus, friction coefficient, and restitution coefficient). In comparison with the study of the variables in the first group, the study of variables in the second group, particularly friction and restitution coefficients, is few, as briefly reviewed below.

In general, friction coefficient is important in dense-phase flow, whereas restitution coefficient is important in dilute-phase flow. In the past decades, to be quantitative, various experimental techniques have been developed to directly measure particle–wall interaction in low-velocity dense-phase pneumatic conveying and generate useful information about the wall friction (see, for example, [2,3]). At the same time, some experimental studies coupled with theoretical analysis have also been made to quantify the contribution of the wall friction to the pressure drop in both dense- and dilute-phase pneumatic conveying, as respectively summarised by Mabrouk et al. [4] and Pahk et al. [3]. However, there are limited experimental efforts made to study the effect of restitution coefficient. Such efforts mainly focused on linking particle–wall interaction to restitution coefficient for modelling dilute-phase pneumatic conveying [5,6]. Overall, because it is not easy to change the friction or restitution coefficient while fixing other properties, quantitative studies of these two coefficients are difficult in physical experiments. In principle, this difficulty can be overcome by numerical simulations that are often carried out under well-controlled conditions [7–9].

Numerical models may be continuum- or discrete-based with respect to particles or the solid phase here. The former is typically represented by the so-called two-fluid model (TFM) [10–13]. This approach is suitable for process modelling and applied research because of its computational convenience and efficiency. The previous numerical studies suggested that the frictional and inelasticity effects are important in many systems such as hopper, chutes and fluidized beds [7]. However, only a few TFM studies were made in the past to investigate the effects of material properties on pneumatic conveying, largely limited to dilute-phase flows. For example, Hadinoto and Curtis [10–12] found that inelasticity and lubrication effects characterised by restitution coefficient can be as important as turbulence modulation or particle–fluid interaction for dilute turbulent particle–fluid (air or

* Corresponding author. Tel.: +61 2 93854429; fax: +61 2 93855856.
E-mail address: a.yu@unsw.edu.au (A.B. Yu).

0032-5910/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.powtec.2013.10.013

liquid) flows through vertical pipes, and proper modelling of the lubrication effect can significantly improve the model predictive capability at relatively low particle Stoke number. Zhu et al. [13] showed that the effect of particle–wall restitution coefficient on solid distribution is significant for relatively large particles but insignificantly for small particles in horizontal pneumatic conveying. In all these studies, particles were assumed frictionless.

The discrete-based approach is typically represented by the combined approach of computational fluid dynamics and discrete element method (CFD–DEM) or the Lagrangian particle tracking (LPT) [8,9]. The latter can be thought as a simplified CFD–DEM model when the solid concentration is close to zero. The CFD–DEM approach has been increasingly used to study pneumatic conveying [9]. However, only a few studies considered the effects of material properties and the resulting results are not comparable. For example, some studies suggested that both friction and restitution coefficients marginally affected the solid flowrate in vertical and inclined pneumatic conveying [14,15]. Conversely, others demonstrated that both friction and restitution coefficients may affect particle flow pattern and gas pressure drop in horizontal pneumatic conveying [16,17]. Nonetheless, all of the previous CFD–DEM studies on the effects of material properties were conducted mainly to test model sensitivity, with limited results generated. To date, our understanding of the effects of friction and restitution coefficients is so little that they are rarely seriously considered in the design and operation of a pneumatic conveying system.

This paper presents a comprehensive study of the effects of the friction and restitution coefficients on the flow behaviours in horizontal pneumatic conveying by means of a three-dimensional CFD–DEM method. A series of cases with particles of different friction and restitution coefficients are simulated at different gas velocities for a constant solid flowrate. The results are examined in terms of flow properties such as particle flow pattern, pressure drop, solid concentration, and particle velocity. The flow transitions between different flow regimes due to the change of friction and restitution coefficients are also investigated. The findings should be useful not only for establishing a comprehensive picture about the effects of friction and restitution coefficients but also for designing and controlling pneumatic conveying systems.

2. Simulation method

The CFD–DEM model used in the present study has been detailed elsewhere [16]. A comprehensive study of the theories behind this method can be found in the recent work of Zhou et al. [18]. For brevity, therefore, we only describe the key features of the model below.

2.1. Governing equations for particle flow

The solid phase is treated as a discrete phase described by DEM, where the translational and rotational motions of a particle can be respectively described by the following equations:

$$m_i \frac{d\mathbf{v}_i}{dt} = \mathbf{f}_{pgf,i} + \mathbf{f}_{drag,i} + \sum_{j=1}^{k_i}\left(\mathbf{f}_{c,ij} + \mathbf{f}_{d,ij}\right) + m_i\mathbf{g} \tag{1}$$

and

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_{j=1}^{k_i}\left(\mathbf{T}_{t,ij} + \mathbf{T}_{r,ij}\right) \tag{2}$$

where m_i, I_i, $\mathbf{v}_i$ and $\boldsymbol{\omega}_i$ are the mass, moment of inertia, translational and angular velocities of particle i, respectively. According to Zhou et al. [18], the main forces involved in the particle–fluid flow modelling are: (1) the pressure gradient force, given by $\mathbf{f}_{pgf,i} = -\nabla P V_i$, where P and V_i are the fluid pressure and the volume of particle i, respectively; (2) the fluid drag force, calculated by $\mathbf{f}_{drag,i} = \mathbf{f}_{drag0,i}\varepsilon_{f,i}^{-\chi}$, where $\mathbf{f}_{drag0,i}$ and ε_f are the fluid drag force on particle i in the absence of other particles and the local porosity for the particle respectively [19]; (3) the gravitational force $m_i\mathbf{g}$; and (4) the inter-particle forces between particles i and j, which include the elastic contact force $\mathbf{f}_{c,ij}$, and viscous contact damping force $\mathbf{f}_{d,ij}$. Trial simulations indicate that other particle–fluid forces such as the virtual mass force, lift force and viscous force could be ignored in this work. The torque acting on particle i due to particle j includes two components. One arises from the tangential forces given by $\mathbf{T}_{t,ij} = \mathbf{R}_{i,j} \times (\mathbf{f}_{ct,ij} + \mathbf{f}_{dt,ij})$, where $\mathbf{R}_{i,j}$ is a vector from the centre of mass to the contact point, and another is the rolling friction torque given by $\mathbf{T}_{r,ij} = \mu_{r,ij} d_i \left|\mathbf{f}_{n,ij}\right| \hat{\boldsymbol{\omega}}_{t,ij}$, where $\mu_{r,ij}$ is the (dimensionless) rolling friction coefficient and d_i is particle diameter [20]. The second torque is attributed to the elastic hysteresis loss and viscous dissipation in relation to particle–particle or particle–wall contacts, and it causes the decay in the relative rotational motion of particles. For viscoelastic material, it has been recently reported that $\mu_{r,ij}$ together with other parameters of DEM simulation can be evaluated as a function of material properties [21]. For a particle undergoing multiple interactions, the forces and torques are summed over the k_i particles in contact with particle i. The inter-particle and particle–wall forces given in Table 1 are calculated based on the non-linear models commonly used in DEM [8].

2.2. Governing Equations for Gas Flow

The gas flow is treated as a continuous phase and modelled in a similar way to the one in the conventional two-fluid modelling. As noted by Zhou et al. [18], three model formulations are available. This work adopts the so-called original model B or type I model, where the pressure is regarded to be due to gas alone. Thus, its governing equations are the conservation of mass and momentum in terms of local mean variables over a computational cell, given respectively by,

$$\frac{\partial\left(\rho_f \varepsilon_f\right)}{\partial t} + \nabla\cdot\left(\rho_f \varepsilon_f \mathbf{u}\right) = 0 \tag{3}$$

and

$$\frac{\partial\left(\rho_f \varepsilon_f \mathbf{u}\right)}{\partial t} + \nabla\cdot\left(\rho_f \varepsilon_f \mathbf{u}\mathbf{u}\right) = -\nabla P - \mathbf{F}_{\text{p-f}} + \nabla\cdot\left(\varepsilon_f \boldsymbol{\tau}\right) + \rho_f \varepsilon_f \mathbf{g} \tag{4}$$

where ρ_f, $\mathbf{u}$, P, $\boldsymbol{\tau}$ and $\mathbf{F}_{\text{p-f}}$ are the fluid density, fluid velocity and pressure, fluid viscous stress tensor, and the volumetric forces between particles and fluid, respectively. Note that $\mathbf{F}_{\text{p-f}} = \sum_{i=1}^{k_c}\left(\mathbf{f}_{drag,i} + \mathbf{f}_{pgf,i}\right)/\Delta V$, where k_c and ΔV are the number of particles in a considered computational cell and the volume of the computational cell, respectively. $\boldsymbol{\tau}$ is given by an expression analogous to that for a Newtonian fluid. That is

$$\boldsymbol{\tau} = \left(\eta_{\text{laminar}} + \eta_{\text{turbulent}}\right)\left[(\nabla\mathbf{u}) + (\nabla\mathbf{u})^{-1}\right] \tag{5}$$

where η_{laminar} is fluid molecular viscosity, and $\eta_{\text{turbulent}} = C_\mu \rho_f k^2/\varepsilon$ is the turbulent viscosity and is calculated using a standard k–ε turbulent model combined with a standard wall function [22]. The turbulence of

Table 1
Material properties used in the present study.

Parameter	Value	Parameter	Value
Shape	Spherical	Poisson's ratio, ν	0.33
Diameter, d (m)	0.003	Restitution coefficient, e	0.9 (0.5–0.9)
Density, ρ_p (kg/m^3)	1000	Sliding friction coefficient, μ	0.5 (0.1–0.9)
Young's modulus, Y (Pa)	1.0×10^8	Rolling friction coefficient, μ_r	0.02

NB: these are for the base case, with the varying range of a few parameters in parentheses.