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An engineering model of dilute polydisperse pneumatic conveying

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Abstract

A model for a gas-polydispersed particle flow in a pipeline is presented. The chaotically moving particles of different sizes are represented as sets of granular gases having different granular temperatures. The latter are generated due to partial momentum loss of particle–wall collisions as well as due to collisions of particles of different sizes with each other, and dissipated because of partially inelastic particle–particle collisions and also due to the particle–gas viscous friction. The model developed has been validated by comparison of the calculated pressure losses with the experimental data. The granular temperatures calculated by the model have been compared to those computed by the molecular dynamics code. A comparison is also made on the effect of polydispersity on pressure losses.

Keywords: Gas flow; Pneumatic systems; Particle interactions; Particle motion; Pressure reduction; Solids flow

1. Introduction

To the best of our knowledge, most models describing pneumatic transport are developed for the monodispersed solids. In practice, however, particulate materials are almost always polydispersed and thus the effect of it on, for example, pressure drop should be of interest.

Usually researches treat the solid phase either as a continuum [1–3] or as a discrete system [4–6].

The continuum model approach is based on the hypothesis of a granular gas. Accordingly, particles are considered as gas molecules moving chaotically. In general, a granular gas possesses granular pressure, temperature, viscosity and conductivity. These parameters are calculated using correlations [2] similar to those known from the molecular fluid dynamics. Stresses arising in a granular media due solids-pipe wall friction cause major pressure losses. In the often-cited paper [1] authors simulate the axis-symmetrical vertical gas–particle flows using such an approach. The computed distributions of gas and particle velocities as well as the axial pressure gradients are in good agreement with the experimental data. One of the model drawbacks is the method of calculating the shear stresses on the wall and the corresponding granular energy source. This is because this method is based on the Coulombic friction between the particles and the wall and therefore is not accurate enough if the wall micro-roughness is comparable with the particle size.

In the discrete approach the particles move separately and interact with each other [4]. From the computational viewpoint, this approach is restricted to the relatively small number of particles.

According to another discrete method, separate particle trajectories are calculated by the Lagrangian approach while particle–particle collisions are considered as a random process. It is assumed that a particle moves in a cloud formed by other particles. The motion through this cloud is accompanied by collisions with particles forming this cloud. This approach allows calculating the conveying pipes with a reasonable accuracy [5,6].

Herein we present a simple model of polydispersed gas–particle flow in a pipeline based on a continuum approach. The model is a one-dimensional one and is suitable for fast and reliable estimations of solids velocities and pressure losses in diluted conveying flows.

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2. The model

In engineering applications the problem of pneumatic conveying calculations is usually reduced to determining the pressure gradient.

We employed the basic ideas of the known kinetic approach [2] to simulation of gas–particle flows according to which the particles medium is represented as a continuum possessing granular temperature, pressure, viscosity, etc. Particles are treated like molecules in a real gas.

We assume that the friction losses are associated with the momentum loss of the solid phase caused by multiple particles collisions with the wall. For describing solids momentum losses we introduce the tangential restitution coefficient [7,3], which equals the ratio of an axial component of the particle momentum after the collision with the wall to that before the collision:

$$k_t = \frac{m_p u_p'}{m_p u_p} \qquad (1)$$

where m_p is the particle mass and u_p, u_p' are the axial component of the particle velocity before and after the collision with the wall, respectively.

The coefficient k_t is a function of the particle and the pipe materials, the pipe surface roughness, the particle shape, and the angle under which the particle collides with the wall. It is clear that only the angle of collision depends on a flow regime. This angle is small and changes in a narrow range. Louge et al. [1] showed that the normal component of the particle–wall collision velocity is practically always within several percent of a particle axial velocity. Thus, the tangential restitution coefficient can be considered as being independent of process parameters, i.e. it is a function of particle material and pipe surface properties only. In applications, this coefficient can be found from a couple of experiments providing the best fit of simulated data to experimental ones.

We consider the friction losses in a flow with uniform (averaged) gas and particle parameters across the pipe, i.e. we develop a one-dimensional flow model. This approximation is justified for the following reasons. In many regimes of dilute pneumatic conveying the cross-sectional distribution of solids velocity is close to uniform (for example, Louge et al. [1]) and therefore particles collide with the wall along the whole pipe perimeter possessing the same axial velocity components. The question is whether this assumption is applicable to the case when the solids concentration in a horizontal flow varies along the pipe height due to gravity. Our estimations show that the mean particles chaotic velocity is almost inversely proportional to the volumetric solids concentration. As it will be clear from the equations presented below, the axial pressure gradient is a function of the frequency of particles–wall collisions. This frequency, in turn, is a linear function of the product of the root-mean-square of particle chaotic velocity and the solids concentration (see Eq. (9)). Thus, when the concentration increases the mean particle chaotic velocity decreases keeping their product practically constant. Thus, the one-dimensional approximation of gas–solids flow based on averaged parameters is justified even for considerably non-homogeneous flows.

Note also that we neglect the influence of turbulent fluctuations on particles because for dilute pneumatic conveying regimes the time scale of the slowest turbulent eddies is much smaller than the particle relaxation time (if particles are larger than d_s = 100–200 μm). In our model we also ignore the particle rotation, based on the results presented by Louge et al. [1], where a good agreement between the numerical and experimental data was obtained for gas–solids flows in pipes. Moreover, because in practice the particle shape is not an ideal sphere, taking rotation into account can be an unjustified model complication. We also neglect both Magnus and Saffman forces acting on solids because our evaluations show that these forces are negligibly small when relatively large particles are conveyed.

Note that the particle lift effect due to the Magnus force caused by particle rotation could not be accounted for within the continuum approach even if the particle rotation was taken into account. This is because the direction of the Magnus force depends on the direction of a particle rotation that cannot be controlled using the kinetic (continuum) theory. Moreover, according to Crowe et al. [8] there are no reliable correlations for the Magnus lift coefficient at high particle Reynolds numbers based on the rotational motion and this problem requires further investigations. We would like to emphasize that on the basis of the comparative analysis of the experimental data [9] and the results of computations based on continuum approach, Eskin [10] showed that the Magnus effect is negligible for dilute pneumatic conveying of relatively large particles (>100 μm).

2.1. Basic equations

The equation of mass conservation for a gas is written as

$$J_g = \rho_g u_g (1-\varepsilon) \approx \rho_g u_g = \text{const.} \qquad (2)$$

where J_g is the gas mass flow rate per unit area, u_g the gas velocity, and ρ_g is the gas density.

Note that in Eq. (2) we neglected the particle volumetric concentration because we consider dilute flows.

Let us represent a polydispersed particle system as a set of discrete monodispersed fractions $i = 1, \ldots, n$.

The equation of mass conservation for a solid phase fraction has the form:

$$J_i = \rho_p \varepsilon_i u_i = \text{const.} \qquad (3)$$

where u_i is the solid velocity of the particles in the ith fraction, J_i the solids mass flow rate per unit area, ε_i the solid volumetric concentration, and ρ_p is the particle density.

Note, although a flow with low velocities, typical for pneumatic conveying, behaves as incompressible locally; a pressure loss in a long pipeline can be significant resulting in a considerable decrease in density thus causing increase in a flow velocity. This decrease in density can be taken into account by the equation of state for the gas. Since a gas temperature usually does not change along the pipeline the equation of state for an isothermal