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Particle-laden gas flow in horizontal channels with collision effects

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Abstract

A model is presented for the behavior of solid particles in a turbulent horizontal channel flow. Eulerian equations are used in the calculations for the fluid and the polydisperse solid phase. Inter-particle collisions are taken into account that includes two mechanisms: collisions with sliding friction and collisions without sliding friction. Particulate collisions are accounted for by taking into account the collisions due to the difference in the average motion of the various fractions and, also, by the collision due to the particle fluctuating motion caused by the gas turbulence. In addition to the closure equations for the mass and momentum conservation, based on inter-particle collision, this model incorporates an original description of the particle motion in a horizontal channel, by introducing the decomposition of the particle-phase motion into two particle-phase flows: falling and rebounding particle flows. This allows the proper calculation of the wall influence on the particles' motion by accounting for the long-range disturbances of the transverse velocity of the rebounding particles, which are computed with the help of the restitution coefficients. The model has been validated by comparison with the experimental data of Tsuji and Morikawa [Y. Tsuji, Y. Morikawa, LDV measurements of an air-solid two-phase flow in a horizontal pipe. J. Fluid Mech., 120 (1982) 385–409.] for loading ratios up to 50 conveyed by low magnitude gas-phase velocity of 6 to 15 m/s and with the experimental data of Laats and Mulgi [M. Laats, A. Mulgi, Experimental study of the kinematic process of the motion of small solid particles in turbulent flow in the pipe. Proc. 3-rd all-union conference on theoretical and applied issues in turbulent flows (II part). *Turbulent Two-phase Flows*, Tallinn, ed. Estonian Acad. Sci., (Estonia) (1979) pp. 32–36.], which used higher value of gas-phase velocity of 50 m/s.

Keywords: Channel flow; Collisions; High loading ratio; Turbulence; Polydisperse

1. Introduction

Particulate transport by a carrier fluid is a frequently used process in the chemical industry, oftentimes called pneumatic conveying. This type of process is influenced by several physical phenomena, such as particle sedimentation, inter-particle collisions as well as lift and drag forces, caused by the interaction of particles with the walls. The combination of these phenomena results in an asymmetric flow in horizontal channels. The experiments by Tsuji and Morikawa [1] showed that a decrease of the magnitude of mean flow velocity leads to an increased asymmetry of the average longitudinal velocity. The same experiments also showed that a minimum mean flow velocity must be maintained for the particles to be transported. The magnitude of the minimum transport velocity was also discussed by Davies [3] and Cabrejos and Klinzing [4].

Of the recent studies in horizontal pneumatic conveying, Sommerfeld [5] presented a number of diagrams for the average and r.m.s. velocity shapes, which were obtained for a relatively large mean flow velocity, with no noticeable effect on the velocity profiles due to the particle accumulation on the bottom wall. Sommerfeld and Zivkovic [6] estimated the effect of the particles' collision on a stochastic approach using a Lagrange frame of reference. The stochastic approach for the particles' collision model was also considered by Oesterle and Petitjean [7] as well as by Yamomoto et al. [19]. The calculations in the last three studies were restricted to short pipe lengths. In similar studies, Simonin and coworkers [8,9] have used the pdf approach, within the frame of the two-fluid model, to model gas-solid flows with collisions.

The effect of inter-particle collisions is obviously important for dense particulate flows where the ratio of particle response time is larger than the time of inter-particle collisions that is when $\tau/t_c>1$ with $\tau=\left(\frac{18\rho\nu}{\rho_p d^2}C_D\right)^{-1}$ being the particle response time.

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The frequency of particulate collision $f_c = 1/t_c$ may be calculated by the classical expression of Marble (1967): $f_c = \left(\frac{d_i+d_j}{2}\right)^2 |\vec{V}_i - \vec{V}_j| n_{ij}$, where d_i and d_j are the diameters of colliding particles, V_i and V_j are the velocities of the particles and n_{ij} is the concentration (number of particles per unit volume) of the group of particles "j," which may collide with the group of particles "i." An order of magnitude estimate shows that the inequality $\tau/t_c > 1$ is satisfied when the mass loading is higher than 10. Hence, inter-particle collisions play an important role in the transport processes when the loading ratio is higher than 10.

There are a few particle collision models obtained in a Eulerian frame of reference, such as the ones by Louge et al. [10], and Cao and Ahmadi [11]. In this paper, we also apply a two-fluid approach using a two-way coupling model. We introduce a collision model that considers the exchange of not only the linear momentum, but also the angular momentum. Hence, we obtain analytical formulae for the stress tensor components and the pseudoviscosity coefficients, using an average procedure over the collision coordinates.

It is well known that the presence of particles induces changes of the turbulence structure in the carrier fluid. This is described by a number of models, such as the ones by Danon et al. [12], Elghobashi and Abou-Arab [13], Chen and Wood [14], Pourahmadi and Humphrey [15], Shraiber et al. [31]. Yuan and Michaelides [16] suggested several mechanisms for the modulation of turbulence in a gas–solids mixture. Crowe and Gillandt [17] incorporated these mechanisms in a quantitative particulate transport model and derived expressions that predict both turbulence enhancement and attenuation in terms of the velocity slip between the phases. In our models for the transport of particles, we use this model for turbulence modulation, because it agrees well with the experimental results of Tsuji and his coworkers [1,18] both for the upward and for the horizontal gas–solid particulate channel flows.

Together with the collisions and turbulence modulation mechanisms, the effect of lift forces using the expression for the Magnus lift that results from the rotation of the particles, as was presented by Yamomoto et al. [19], and Feng and Michaelides [20]. This force, in combination with high longitudinal velocities, is strong enough to cause the suspension of the particles in horizontal flows.

This paper presents the governing and closure equations for the turbulent flow of a gas–solids mixture in a horizontal channel. The model has been validated by comparison with experimental data at intermediate and high mass loading ratios (up to 50) and for particles of various sizes in the range of diameters $0.1 < d < 1$ mm. The results show the modification of the flow structures revealing the asymmetry of the average and r.m.s. velocity profiles even at reasonably high transport velocities of the carrier fluid. The model also shows the importance of accounting for the inter-particle collisions in the case of intermediate and high mass ratios.

2. The gas-particle flow model

2.1. Governing equations of the carrier gas-phase

The governing equations for the carrier and the particle solid phases ($i = 1, 6$) are written for a boundary layer flow. We use the four-way coupling approach of Crowe et al. [21], where the gas-particle and inter-particle force factors are included in the k-equation for the turbulent kinetic energy. Since the motion of particles in a horizontal channel is subject to the gravitational settling, there is an asymmetry in the flow for both gas and particle profiles. The conservation equations for mass, momentum and turbulent energy together with the closure expressions for the coefficient of the turbulent viscosity of gas, v_t, and the turbulence length scale, L_h, are as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial p}{\rho \partial x} + \frac{\partial}{\partial y}(v + v_t)\frac{\partial u}{\partial y} - \sum_{i=1}^{6} \alpha_i \frac{C'_{\mathrm{Di}}}{\tau_i}(u - u_{si}), \tag{2}$$

The combined solution of Eqs. (1) and (2) is the following momentum equations in an integral form:

$$\frac{\mathrm{d}p}{\rho \mathrm{d}x} = \int_0^h \left\{ \left[\frac{\partial}{\partial y}(v + v_t)\frac{\partial u}{\partial y}\right] - \frac{18\rho v}{\rho_p d_i^2}\alpha_i C_{\mathrm{Di}}(u - u_{si}) \right\} \frac{\mathrm{d}y}{u^2} \Big/ \int_0^h \frac{\mathrm{d}y}{u^2}, \tag{2a}$$

and

$$v = u \left\{ \frac{-\int_0^h \left[\frac{\partial}{\partial y}(v + v_t)\frac{\partial u}{\partial y}\right]\frac{\mathrm{d}y}{u^2} + \frac{\mathrm{d}p}{\rho \mathrm{d}x}}{\int_0^h \frac{\mathrm{d}y}{u^2} + \frac{18\rho v}{\rho_p d_i^2}\int_0^h \alpha_i C_{\mathrm{Di}}(u - u_{si})\frac{\mathrm{d}y}{u^2}} \right\}. \tag{2b}$$

The turbulence kinetic energy and other closure equations, may be written as follows:

$$\begin{aligned} u\frac{\partial k}{\partial x} + v\frac{\partial k}{\partial y} &= \frac{\partial}{\partial y}(v_t + v)\frac{\partial k}{\partial y} + v_t\left(\frac{\partial u}{\partial y}\right)^2 - v\left(\frac{\partial \sqrt{k}}{\partial y}\right)^2 \\ &+ \sum_{i=1}^{6} \alpha_i \frac{C'_{\mathrm{Di}}}{\tau_i}\left\{\left[(u - u_{si})^2 + (v - v_{si})^2\right] - \sum \langle u'_{si} u' \rangle|_{\mathrm{turb}}\right\} \\ &- \frac{k\sqrt{k}}{L_\mathrm{h}}, \end{aligned} \tag{3}$$

$$v_t = C_{\mu t}\sqrt{k L_\mathrm{T}}, \tag{4}$$

$$L_\mathrm{h} = 2L_\mathrm{T}\lambda/(L_\mathrm{T} + \lambda), \tag{5}$$

$$C_{\mu t} = 0.07(L_\mathrm{T}\sqrt{k})\exp\lfloor -2.5/(1 + (L_\mathrm{T}\sqrt{k}/50v))\rfloor, \tag{6}$$

where $\lambda = d_\Sigma \lfloor (\pi\rho_p/6\rho\alpha_\Sigma)^{1/3} - 1 \rfloor$ is the inter-particle space distance $\left(\alpha_\Sigma = \sum_{i=1,6}\alpha_i, d_\Sigma = \frac{1}{\alpha_\Sigma}\sum_{i=1,6} d_i\right) L_\mathrm{T}$ is the integral turbulence length scale, given by the expression $L_\mathrm{T} = \frac{k_0^{3/2}}{\varepsilon_0}$ and d_i represents the diameter in the i-th fraction.