Powder Technology 270 (2015) 358–367

Contents lists available at ScienceDirect

Powder Technology

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

Improvements in the numerical prediction of fully-suspended slurry flow in horizontal pipes

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ARTICLE INFO

Article history:
Received 25 August 2014
Received in revised form 15 October 2014
Accepted 17 October 2014
Available online 31 October 2014

Keywords:
Two-fluid model
Slurries
Fully-suspended flow
Two-phase flow
Pipe flow

ABSTRACT

A new two-fluid model is presented for the simulation of fully-suspended liquid–solid slurry flows in horizontal pipes. The model is a significant upgrade of an earlier one [G.V. Messa, M. Malin, S. Malavasi, Powder Technol. 256 (2014), 61–70], and the main improvements concern the use of: (1) a new wall boundary condition for the solid phase (2) a more general correlation for the viscosity of the mixture, which allows accounting for particle shape; (3) a different solution algorithm, which reduces significantly the already low computational burden. By comparison with experimental data available in the literature regarding sand–water slurries, the model showed wider applicability compared to the earlier one. In particular, the validation was carried out for the following flow conditions: pipe diameter between 50 and 200 mm; particle size between 90 and 640 μm; mean delivered solid concentration up to 40% by volume; and slurry superficial velocity up to 9 m/s. Slurries in which the dispersed phase consists of spherical glass beads have been briefly explored too. The improvements considerably increase the accuracy of the pressure gradient predictions, without affecting the model's capability in reproducing the other features of these flows of most engineering interest, namely solid volume fraction distribution and velocity distribution.

1. Introduction

Pipe flows of solid–liquid mixtures in the form of slurry are commonly encountered in many applications. A significant example is the slurry pipelines used to transport mineral concentrate from a mineral processing plant near a mine. The pressure gradient is perhaps the most relevant parameter to engineers and designers, as it dictates the selection of pump capacity.

Doron and Barnea [1] identified the flow patterns of slurries flowing in horizontal pipes as the flow rate decreases: (a) fully-suspended flow, in which all the particles are suspended; (b) flow with a bed (moving/stationary), in which the particles accumulate at the pipe bottom and form a bed either sliding or fixed. The transition between fully-suspended and bed flows corresponds to a minimum in the plot of pressure gradient, $\Delta P/\Delta z$, versus slurry superficial velocity, V_s, which is the ratio of the slurry volumetric flow rate and the area of the pipe section (Fig. 1). The value of superficial velocity at which the transition occurs is referred to as deposition velocity, V_D, and can be estimated by many empirical formulas including the one proposed by Wasp [2], as follows:

$$V_{D,\mathrm{Wasp}} = 4\left(\frac{d_p}{D_p}\right)^{1/6} C^{1/5}\sqrt{2|\mathbf{g}|\left(\frac{\rho_p}{\rho_f}-1\right)} \qquad (1)$$

where d_p is the particle size, D_p is the pipe diameter, C is the delivered solid volume fraction, $\mathbf{g}$ is the gravity acceleration vector, and ρ_p and ρ_f are the densities of the particles and the fluid, respectively. By comparison against a large dataset of experimental measurements available in the literature, Messa [3] evidenced that Eq. 1 is likely to underestimate the deposition velocity.

In bed flows Coulombic stresses occur among the particles in permanent contact with each other. These stresses are transferred to the pipe wall and produce a solid shear stress which contributes to friction if the layer of particles is not stationary. However, a slurry pipeline is usually run at somewhat higher velocity compared to V_D [4], and therefore being able to correctly predict the behavior of fully-suspended flows is of considerable importance from an engineering point of view. In the present work we will focus on the fully-suspended flow regime. Therefore, we will refer only to the right part of the plot of Fig. 1.

In fully-suspended flows the interactions among the particles are in the form of occasional collisions rather than permanent contacts. The interactions among fluid, particles, and the pipe wall determine the dissipation occurring during the transport of the slurry. It is a well established practice to attribute the pressure gradient of the fully-suspended solid–liquid slurry to two different frictional mechanisms, referred to as viscous "liquid-like" friction and mechanical friction [5]. The former is due to the slurry viscosity in the laminar sublayer, while the latter is due to the impingements of the traveling suspended particles with the pipe wall. These mechanisms are strictly dependent upon the relationship between the particle size and the boundary layer

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http://dx.doi.org/10.1016/j.powtec.2014.10.027
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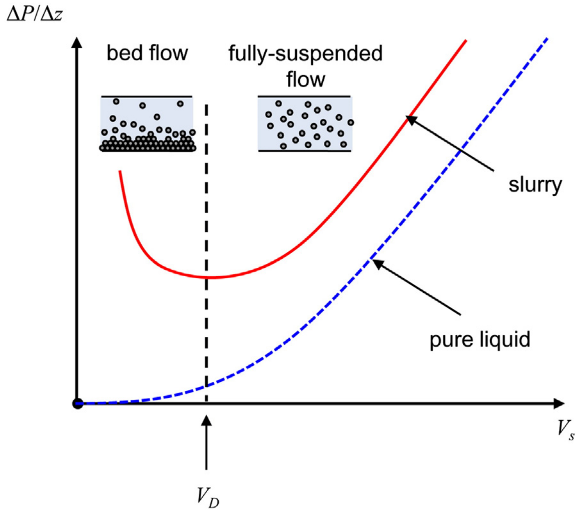

Fig. 1. Qualitative plot of pressure gradient, $\Delta P/\Delta z$, versus slurry superficial velocity, V_s. Identification of the flow regimes and comparison against the single-phase case.

characteristics which, in some previous researches [6-8], was quantified by means of a dimensionless particle size:

$$d_p^+ = \frac{\rho_f d_p u_f^*}{\mu_f} \tag{2}$$

where u_f^* is the friction velocity of the fluid, namely the square root of the ratio between the fluid wall shear stress $\tau_{w,f}$ and the fluid density ρ_f, and μ_f is the dynamic viscosity of the fluid.

If the particles are small enough to be trapped within the viscous sublayer (say for $d_p^+ \ll 5$), they increase the density and the viscosity of the carrying fluid. This determines an increase of the viscous "liquid-like" friction which, in turn, results in higher pressure gradient compared to the single-phase case. Conversely, the mechanical contact friction does not play a role unless the concentration of solids near the wall becomes very high. As a consequence of the above, under these conditions the pressure gradient can be estimated using an "equivalent-fluid" model in which the slurry is interpreted as a single-phase fluid with increased density and viscosity.

Slurries with particles which are larger compared to the thickness of the viscous sublayer, which are the topic of this paper, exhibit a completely different behavior. In this case, the particles do not affect the fluid dynamic properties of the carrying fluid in the viscous sublayer, and the impingements between the particles and the pipe wall become significant. The impingements are a result of the dispersive action of both turbulence and particle collisions, and generate a solid dispersive wall shear stress $\tau_{w,p}$ which acts in conjunction with the liquid-like friction.

Due to the considerable interest that slurry flows arouse, especially in the field of mining industry, several models have been developed for the estimation of $\tau_{w,p}$ starting from bulk parameters like the slurry superficial velocity V_s, the pipe diameter D_p, and the characteristics of the mixture. These models are usually derived from a generalization of the original equation for Bagnold's stress in the inertial regime of the sheared annular flows and calibrated by using pressure-drop data. The following correlation, proposed by Ferre and Shook [9], includes the key functional dependencies:

$$\frac{\tau_{w,p}}{\rho_s V_s^2} = 0.0214 Re_s^{-0.36} \left(\frac{d_p}{D_p}\right)^{0.99}{}^{1.31} \tag{3}$$

where Re_s is defined as $\rho_s V_s d_p/\mu_f$ and λ is the linear volume fraction:

$$= \left[\left(\frac{\alpha_{\max}}{C}\right)^{1/3} - 1\right]^{-1} \tag{4}$$

in which $\alpha_{\max}$ is the maximum packing volume fraction. A similar expression, accounting for the dependence upon λ only, was proposed by Gillies and Shook [10] some years later. Other and more recent correlations are those of Matousek [11], Gillies et al. [7], and Bartosik [12]. It is worth noticing that the above mentioned formulas for $\tau_{w,p}$ have been developed to be employed as part of physically-based models based on a global formulation for the estimation of the pressure gradient.

Moreover, anomalous pressure gradients and volume fraction distributions have been observed in some experiments [13-16]. In order to explain these findings, some authors argued for the existence of a hydrodynamic lift force repelling particles from the walls, which is effective only when the center of the particles lies in a certain band of distances from the wall. Actually, the origin of this force, which increases with the delivered solid volume fraction, is still rather obscure. Wilson and Sellgren [17] attribute it to the interaction between a solid particle and liquid flow of the steep velocity gradient, which causes its rotation and develops a pressure differential over the particles. They developed a model for this force, later revised by Wilson et al. [8], and reported that, for sand–water slurries, the hydrodynamic lift force is not effective for particles smaller than about 150 μm and larger than about 400 μm. The effect of the hydrodynamic lift force was also observed in slurries made of water and glass beads of 440 μm size [15].

The use of CFD techniques for the simulation of solid–liquid slurry flows is gaining ground in recent years, not only because of the greater information about the structure of the flow that can be gathered, but also because of the versatility of this approach, which virtually allows simulating whatever kind of system at whatever scale. The Eulerian–Eulerian models, referred to as "two-fluid" models, are the only ones which allow simulating dense flows with acceptable computational cost. These models interpret both phases as interpenetrating continua and solve for their average flow properties. The two-fluid model that we proposed in a previous work [6] showed comparable or better agreement with the experimental evidence than similar models [18-21], and it also overcame the main limitations inferred from inspection of these earlier papers, namely susceptibility to numerical instability and high computational cost. In particular, it was capable in predicting the pressure gradient data of different experimenters [7,22,23] within about ±20% of the measured values (Fig. 2). In a later stage of our research, this two-fluid model was successfully applied to more complex geometries, such as sudden expansions [24], pipe bends [25], and choke valves [26].

Nevertheless, further research had to be carried out regarding certain aspects – common to all two-fluid models and not exclusive to ours – of modeling rather than numerical nature. For example, none of the existing models takes explicitly into account the effect of particle shape, which proved to affect significantly the behavior of the slurry [22]. Moreover, the wall boundary condition for the solid phase, which is a key parameter for correctly predicting the pressure gradient, is not well established. This is one of the most restricting uncertainties in the use of the two-fluid models in multiphase simulations [27,28]. In slurry pipe flow computations different options have been considered. Ekambara et al. [19] set the velocity of the particles to zero at the pipe wall, but only briefly explored the capacity of their model to reproduce the pressure gradient. Kaushal et al. [21] applied the standard wall function of Launder and Spalding [29] for single-phase flows to both phases when modeling the pipeline flow of fine particles at high concentration, without reporting the equations actually solved. Chen et al. [18] employed the wall boundary conditions developed by Johnson and Jackson [30] for predicting the flow properties of slurries with solid particles having a bimodal distribution. The same choice was done by Jiang and Zhang [31] who analyzed the flow of a mixture of solid nitrogen particles and liquid nitrogen in a horizontal pipe.

Krampa-Morlu et al. [32] studied the effect of the solid phase boundary conditions on the head loss predictions for dense liquid–solid flows in a vertical pipe using a two-fluid model. The authors investigated the no-slip condition, the free-slip condition (i.e. zero wall shear stress),