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Numerical prediction of fully-suspended slurry flow in horizontal pipes

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ABSTRACT

Turbulent solid–liquid slurry flows in horizontal pipes are encountered in many engineering fields, such as mining, chemical and petroleum. In many applications, turbulence is effective in keeping all the solids suspended, preventing particle accumulation. A two-fluid model for predicting the main features of fully-suspended slurry flows, namely pressure gradient, solid–volume-fraction distribution, and velocity profile, is presented. The model is robust and numerically stable, and requires relatively low computer time to provide converged steady-state solutions. The novelty of the proposed model and its better performance compared to similar ones resides in the method of accounting for some key physical mechanisms governing these flows, namely turbulent dispersion, interphase friction, and the mechanical contribution to friction. The performance of the model is checked by comparison with experimental data available in the literature over a wide range of operating conditions: pipe diameter between 50 and 150 mm; particle size between 90 and 520 μm; mean delivered solid concentration up to 40% by volume; and slurry superficial velocity between 1 and 7 m/s. The dispersed phase consists of either sand or spherical glass beads.

1. Introduction

Pipe flows of solid–liquid mixtures in the form of slurry are commonly encountered in many applications, in the field of both civil and industrial engineering. Pressure gradient and concentration distribution have been the most serious concern of researchers, as they dictate the selection of pump capacity and may be used to determine parameters of direct importance (mixture and solid flow rates) as well as secondary effects like wall abrasion and particle degradation.

The flow of solid–liquid mixtures is very complex. Doron and Barnea [1] identified the flow patterns that characterize the flow of slurries through horizontal pipes. If the flow rate is sufficiently high, turbulence is effective in keeping all the solids suspended (fully suspended flow); otherwise the particles accumulate at the pipe bottom and form a packed bed, either sliding (flow with a moving bed) or not (flow with a stationary bed). The transitions between flow patterns are not always clear and they are usually identified by post-processing measured data in terms of solid–volume-fraction profile and pressure gradient [2]. In particular, the transition between fully-suspended and bed flows corresponds to a minimum in the plot of pressure gradient versus slurry superficial velocity (which is the ratio between the volumetric flow rate of the two-phase mixture and the area of the pipe section), qualitatively depicted in Fig. 1. The threshold velocity between the two regimes is usually referred to as the deposition velocity. Several correlations – usually of an empirical nature – have been developed for roughly estimating the deposition velocity: an overview is reported by Albunaga [2] and Pecker and Helvaci [3]. As an example, the formula of Wasp [4], which is one of the simplest and most frequently cited in the literature, is given below:

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

where: V_D is the deposition velocity; d_p is the particle size; D_p is the pipe diameter; C is the delivered solid volume fraction; $\mathbf{g}$ is the gravitational acceleration; and ρ_f and ρ_p are the density of the fluid and particles respectively.

The present work focuses on fully-suspended flow, and so the considerations reported below hold when turbulence is effective in keeping all the solids suspended. The pressure gradient of the solid–liquid slurry is generally higher than that of an equal flow rate of pure liquid because the particles produce additional dissipation. Actually, the way in which the particles affect the dissipation is a very complex matter, and under specific flow conditions, either negligible variations or even a decrease in losses with respect to the single-phase case was observed [5]. However, this eventuality was not considered here, because it is very rare and pronounced only for vertical pipe flows. The frictional loss of the two-phase flow is considered as a combination of viscous friction and mechanical friction [2,3,6]. The former is due to the liquid viscosity in the laminar sublayer, and is not affected by the solid particles unless they are fine enough to be trapped within the laminar sublayer, which is not the case here. The latter is due to particle–wall interactions which are the result of the dispersive action of both turbulence and particle

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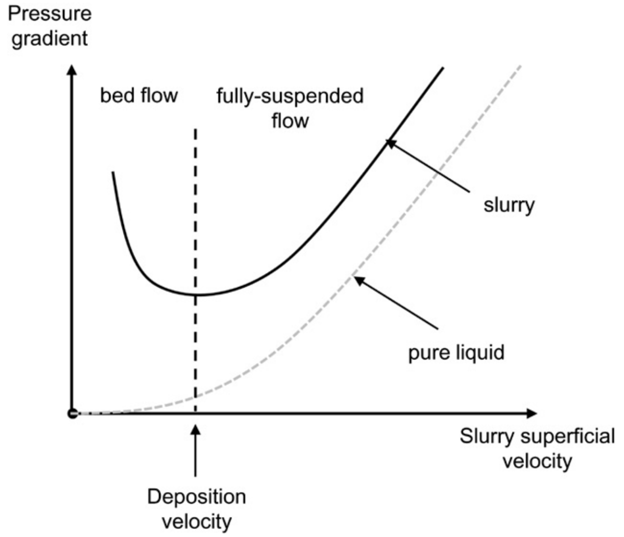

Fig. 1. Qualitative plot of pressure gradient versus slurry superficial velocity. The curve for an equal flow rate of pure liquid is depicted too.

collisions. Some authors have argued for the existence of a hydrodynamic lift force to account for the repulsion of particles from the pipe wall observed in some experiments, which is accompanied by a decrease of the mechanical friction [7]. Wilson and co-workers [8,9] developed a model to account for this effect, but the global nature of its formulation precludes its implementation in a CFD code.

The distribution of the delivered solid volume fraction over the pipe section shows a gradient along the vertical direction arising from gravitational stratification. Fully-suspended flows in which this gradient is clearly detectable are referred to as heterogeneous flows [1]. Conversely, if the slurry superficial velocity is very high, and the effect of gravity is negligible compared to drag and turbulent dispersion, the solid volume fraction can be regarded as uniformly distributed (pseudo-homogeneous flow). Whatever the flow pattern, the solid volume fraction distribution is usually quantified by means of its characteristic vertical profile, which according to the kind of instrumentation used to perform the measurements, is either the profile along the vertical diameter (Fig. 2(a)) or the chord-averaged profile (Fig. 2(b)). Since the variation of the solid volume fraction along each horizontal chord is likely to be small, the two profiles are generally close to each other.

The axial velocity distribution is not univocally defined for a two-phase flow, since it may be represented in terms of either the fluid velocity, the particle velocity, or the mass-averaged mixture velocity. Whatever velocity is considered, unlike that of a single-phase flow, the axial velocity distribution of a solid–liquid mixture is asymmetric with respect to the pipe axis, and the maximum value is shifted towards the upper wall. This behavior was interpreted by Ling and co-workers [10] as a consequence of the fact that, due to the effect of gravity, the slurry density in the lower part of the pipe is higher than that in the upper part. As a result, the fluid spends more energy to drive the particles in the lower part, resulting in a lower slurry velocity in that area. Actually, the asymmetry of the velocity profile is almost undetectable for pseudo-homogeneous flows.

Numerous experimental investigations have been carried out to determine pressure gradients, volume fraction distributions, and less frequently, velocity profiles of slurry flows in horizontal pipes. The dispersed phase is usually sand [6,11–17], but spherical glass beads [18–20], ash [21] and solid nitrogen particles [22,23] have also been considered.

The experimental determination of solid volume fraction and velocity presents considerable technical difficulties. Local values of solid volume fraction can be measured by isokinetic probe sampling, but these techniques may produce significant errors near both the pipe wall [24] and the pipe axis [12]. More accurate results – but with uncertainties of a few percent – are obtained using expensive gamma-ray density gauges, which are used to determine chord-average values of solid volume fraction. The mean concentration of the slurry is characterized in different ways by researchers. Kaushal and Tomita [18,20] and Kaushal et al. [19] considered an overall area-average concentration, evaluated by integrating the local volume fraction profile measured by an isokinetic sampling probe. Matousek [7,13] measured the mean delivered concentration in the pipeline by a counter flow meter. Other authors [14,15] reported values of the mean in-situ concentration, obtained by adding weighted quantities of solids to the loop, whose volume was known. In all cases, the uncertainty about this parameter must be considered when making reference to literature data.

Local values of velocity in slurry flows are commonly measured by the electrical probe developed at the University of Saskatchewan [25] or, less frequently, by Laser Doppler Velocimetry. The former method allows detecting the velocity of the particles, and the main limitation is that the measurements may be affected by the distortion in the flow field produced by the probe, especially close to the pipe walls. The latter method is capable of providing the fluid and particle velocities, but specific procedures are required for discriminating between the two velocities. Numerous examples of applying LDV for solid–liquid flows are reported in the literature [26], but the technique is claimed to be unreliable for concentrated mixtures (mean delivered solid concentration above 15–20% by volume) except homogeneous flows in which the difference in velocity between the phases is small [27].

Simplified models have been developed based on a global formulation to predict macroscopic parameters like the pressure gradient for all flow configurations. The equivalent liquid models apply in the case of fully-suspended flows [3,7], while two- and three-layer models [28–33] may be employed for flows with moving bed and stationary

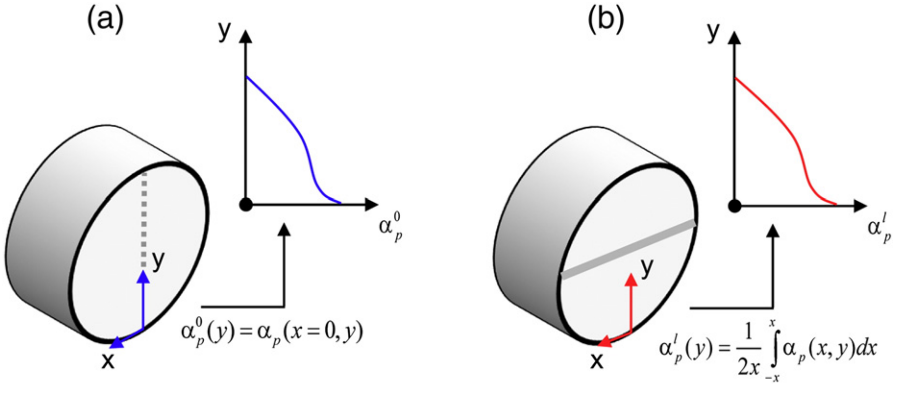

Fig. 2. Solid volume fraction distribution: (a) values along the vertical diameter and (b) chord-averaged profile.