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Horizontal laminar flow of coarse nearly-neutrally buoyant particles in non-Newtonian conveying fluids: CFD and PEPT experiments compared

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ABSTRACT

The horizontal flow of coarse particle suspensions in non-Newtonian carrier fluids was numerically simulated using an Eulerian–Eulerian CFD model. This study was concerned with nearly-neutrally buoyant particles of 5 and 10 mm diameter conveyed by fluids of Ellis rheology in laminar flow, in a 45 mm diameter pipe at concentrations up to 41% v/v. CFD predictions of solid phase velocity profiles and passage times were compared to experimental data obtained by a Positron Emission Particle Tracking (PEPT) technique and Hall effect sensors, and a very good agreement was obtained considering the complexity of the flows studied. CFD predictions of solid–liquid pressure drop were compared to a number of relevant correlations gleaned from the literature. Only one of them showed a good agreement over the whole range of conditions studied. Other correlations generally showed large deviations from CFD, and their limitations in predicting the influence of solids concentration and particle size have been demonstrated. Overall, it emerged that for the flows studied, CFD was capable of giving predictions of pressure drop which were probably better and more reliable than the correlations available in the literature.

1. Introduction

Solid–liquid flow is encountered in a wide variety of situations from hygienic movement and processing of food and pharmaceutical products, through chemicals, oil, mining and construction applications, to the secure transportation of effluent and waste products. Although most applications use water as the carrier medium, there are now many industrial plants, e.g. food, chemical, oil, mining, and power generation industries, where particles are transported in a variety of liquids which may be highly viscous and may exhibit non-Newtonian behaviour. The complexity of these solid–liquid flows is reflected in the number of independent variables generally involved which causes the flow behaviour of these systems to vary over a tremendous range (Abulnaga, 2002). The pipeline (diameter, length, roughness, fittings), the properties of the solids (size and size distribution, shape, density, strength) and of the liquid (density, rheology), and the operating conditions (mixture flowrate, solids concentration) all influence the nature of the flow and the pressure gradient.

Fine particles tend to form reasonably homogeneous suspensions and are usually treated as such. Concentrated suspensions of fine particles may exhibit Newtonian or non-Newtonian behaviour, and are frequently transported in laminar flow where they behave essentially as single phase pseudoplastic (i.e. shear-thinning) liquids, e.g. flocculated kaolin and coal suspensions. Existing models for describing them are based on the principles of continuum mechanics. Thus, pressure drop, for example, is estimated by single phase flow methods using an effective density and viscosity for the suspension (Chhabra and Richardson, 1999).

The vast majority of the documented data on solid–liquid flow relate to water-based slurries of fine particles. There is, therefore, a clear need for experimental data and models to describe the flow of coarse solid–liquid mixtures as they are relevant to a number of industrial applications including the conveying of particulate food mixtures, gravel, and coal lumps. In particular, there is a severe lack of information on the flow of such coarse solid–liquid suspensions in viscous Newtonian and non-Newtonian carrier media. The presence of large particles in a viscous Newtonian or non-Newtonian liquid gives rise to a heterogeneous mixture of complex rheology where the assumption of a continuum as used in fine suspension is clearly inapplicable. Inertial effects, gravitational forces, particle–particle and particle–wall interactions affect the flow of the solid phase giving rise to a different particle behaviour and flow patterns from the carrier fluid.

Viscous Newtonian/non-Newtonian carriers are used because: (a) they are in some cases dictated by the process, e.g. Newtonian heavy oil to transport solids out of wells, and continuous thermal processing of particulate food products in non-Newtonian fluids.

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In the latter case, the process can be subjected to a wide distribution of particle concentrations, velocities, residence times, and temperatures, thereby causing a wide and largely unpredictable distribution of those quality changes that are induced in the food by the heat treatment. The liquid and solid phases sterilise at different times and, therefore, knowledge of the distribution of both liquid and particle velocities/residence times are essential for a sound process design; and (b) when the flow is laminar, the transport of coarse particles in fluids of non-Newtonian rheology offers certain advantages: (i) the apparent viscosity of a shear-thinning fluid is a maximum at the centre of the pipe and this aids particle suspension (though some of this effect may be offset by the propensity of migration across streamlines and the enhanced settling velocities in sheared fluids); (ii) the apparent viscosity is a minimum at the pipe wall, thus, the frictional pressure drop will be low and will increase only relatively slowly with increasing mixture velocity, hence leading to a lower power consumption; and (iii) if the fluid exhibits a yield stress, it tends to assist the suspension of coarse particles in the central region of the pipe (Chhabra and Richardson, 1999).

The use (optional or otherwise) of non-Newtonian carrier fluids for processes which involve conveying of mixtures through pipes has been restricted by a lack of understanding of the behaviour of these flows, and has only been reported in a few studies. Charles and Charles (1971) transported 216 μm sand particles in shear-thinning clay suspensions. The head loss was six times smaller compared to using water. Similarly, Ghosh and Shook (1990) reported a reduction in pressure gradient for the flow of 600 μm sand particles in a shear-thinning CMC solution, but not for 2.7 mm pea gravel particles; this was attributed to the fact that these larger particles were conveyed in the form of a sliding bed and not as a suspension. Duckworth et al. (1983, 1986) conveyed coal particles (up to 19 mm) in a slurry of fine coal which behaved as a Bingham plastic. None of these studies, however, attempted to develop a general method for the prediction of pressure gradient. Chhabra and Richardson (1985) presented a correlation for the prediction of the hydraulic pressure gradient based on experimental data relating to mixtures with a sliding bed. They concluded from a review of the literature that there were insufficient reliable results for expressions to be given for the pressure gradients in other flow regimes. More recently, Gradeck et al. (2005) reported a friction factor chart which groups data acquired using coarse alginate particles (d = 4.4 mm) flowing in Newtonian and non-Newtonian carrier fluids, at solid concentrations up to 15% v/v. The data were fitted by a simple friction factor — Reynolds number correlation.

Experimental studies of laminar solid–liquid flows are scarce and detailed measurements of the flow field and pressure drop in these systems are lacking. Some limited studies used Magnetic Resonance Imaging (McCarthy et al., 1996) or Ultrasound Doppler Velocimetry (Guer et al., 2003). Fairhurst et al. (2001) and Barigou et al. (2003) used Positron Emission Particle Tracking (PEPT) to study coarse (d = 5–10 mm) nearly neutrally-buoyant particles in non-Newtonian CMC fluids and reported information on the solid phase velocity profile and flow regimes within such suspensions. Computational modelling work in this specific area has also been limited. In a rare attempt, Krampa-Morlu et al. (2004) used CFD to predict the flow features of coarse aqueous solid–liquid slurries in turbulent upward flow including velocity profiles. The CFD model, formulated using the software CFX 4.4 (ANSYS Inc.), was tested using the experimental results of Sumner et al. (1990). The particles had a density of 2650 kg m^{-3} and a diameter of 0.47 or 1.7 mm and were simulated at concentrations up to 30% v/v. The authors concluded that the code failed to accurately predict important features of the flow using the default settings.

In this paper, a CFD model, based on the commercial code ANSYS CFX 10.0, is used to study the conveying of nearly neutrally-buoyant coarse particles in laminar non-Newtonian flow in a horizontal pipe. CFD results of the flow field and particle passage times are validated using experimental data obtained, respectively, by PEPT and Hall effect sensors from our earlier work (Barigou et al., 2003; Fairhurst et al., 2001; Fairhurst, 1998), while pressure drop predictions are compared with a number of correlations from the literature. The aim of this work is to evaluate the capability of CFD to predict such complex flows and thus facilitate their modelling for research and industrial design purposes.

2. CFD model of two-phase solid–liquid flow

2.1. Governing equations

The following equations form the basis of the CFD model used to simulate the laminar flow of coarse particles in a non-Newtonian fluid.

2.1.1. Continuity equations

Assuming isothermal flow, a continuity equation can be written for the liquid phase as follows (Van Wachem and Almstedt, 2003)

$$\frac{\partial}{\partial t}(\rho_f C_f) + \nabla \cdot (\rho_f C_f U_f) = 0 \tag{1}$$

and similarly, for the solid phase

$$\frac{\partial}{\partial t}(\rho_s C_s) + \nabla \cdot (\rho_s C_s U_s) = 0 \tag{2}$$

with the constraint

$$C_f + C_s = 1 \tag{3}$$

where the subscripts f and s denote the fluid and solid phase, respectively, C is volume fraction, ρ is density, U is the velocity vector, and t is time.

2.1.2. Momentum equations

The momentum equation for each phase is derived such that it includes, along with the forces acting on that phase, an inter-phase momentum transfer term that models the interaction between the two phases (Van Wachem and Almstedt, 2003); thus for the liquid

$$\rho_f C_f \left[\frac{\partial U_f}{\partial t} + U_f \cdot \nabla U_f\right] = -C_f \nabla P + C_f \nabla \cdot \bar{\bar{\tau}}_f + C_f \rho_f g - M \tag{4}$$

and for the solid

$$\rho_s C_s \left[\frac{\partial U_s}{\partial t} + U_s \cdot \nabla U_s\right] = -C_s \nabla P + C_s \nabla \cdot \bar{\bar{\tau}}_f + \nabla \cdot \bar{\bar{\tau}}_s - \nabla P_s + C_s \rho_s g + M \tag{5}$$

where P is pressure, g is the gravitational acceleration vector, $\bar{\bar{\tau}}$ is the viscous stress tensor, P_s is solid pressure, and M is the interfacial momentum transfer per unit volume made up of the drag force, F_d, and the lift force, F_l. The other forces on the right-hand side of the momentum equations are the pressure force, viscous force, gravitational force, as well as particle–particle interaction force for the solid phase represented by the solid pressure term. The inclusion of this term is particularly important for highly concentrated suspensions (C_s > 0.2) as the interactions increase with solid concentration. This solid pressure term is, therefore, a function of the solid concentration (Gidaspow, 1994), thus

$$P_s = P_s(C_s) \tag{6}$$

and therefore,

$$\nabla P_s = G(C_s) \nabla C_s \tag{7}$$