Complex Internal Fluid Flow Behavior

Santosh Kumar Mishra[1,*],H. Chandra[2],Arun Arora[3]

[1,3]Mechanical Engg. Deptt., Bhilai Institute of Technology
[#1]san810@gmail.com
[2]Department of Mechanical Engg., V.E.C. Lakhanpur, Sarguja University Ambikapur, India 497001
[2]hari-c75@yahoo.co.in

Abstract

The flow of rheologically complex fluids in industrial equipment poses a number of challenges, not least from a modeling point of view. Research is needed to further understand and be able to predict the flow behavior of such materials and to investigate ways of improving their processing. The Non-Newtonian Solid-Liquid fluid flow behavior in horizontal and vertical pipes can be predicted by various methods which are mentioned in the paper. It is proven that Computational Fluid dynamics (CFD) has sufficient capability to deal with such type of flow and was capable of giving predictions of pressure drop which were probably better and more reliable than the correlations available in the literature.

Key Words-CFD; Non-Newtonian fluid: Vibration **Broad-Area**- Mechanical Engineering **Sub-Area-** Fluid Mechanics (Rheology)

1. Introduction

Multiphase flow of solid-liquid mixtures is encountered in a wide spectrum of industrial processes from the chemical, petrochemical, pharmaceutical, food, and biochemical industries, to mining, construction, pollution control, and power generation. Applications include the hygienic movement and processing of food and pharmaceutical products, the transport of coal and ores, and the secure transportation of effluent and waste products. In such systems, solid-liquid mixtures are conveyed in horizontal or/and vertical pipes.

Solid-liquid flows are usually complex and their behavior is governed by a large number of factors, giving rise to a wide range of flow regimes. Among such factors are flow rate, pipe diameter and orientation, carrier fluid physical and rheological properties, and particle size, density and concentration. There is, therefore, an evident need to classify solid-liquid mixtures in order to provide a rational basis for describing their flow behavior.

Classification of solid-liquid mixtures is a long standing theme in fluid mechanics. In one scheme of classification that recurs frequently in the literature, the behavior of solid-liquid mixtures in horizontal pipes is classified into two categories: settling and non-settling slurries. The settling behavior is usually associated with large solid particles, whereas the non-settling behavior is frequently associated with fine particle suspensions (Brown and Heywood, 1991). However, this classification fails to describe the flow behavior of large neutrally or nearly- neutrally buoyant particle suspensions encountered, for example, in the food industry.

Another scheme of classification describes two extremes of slurry behavior based on the physical appearance of the slurry: homogeneous and heterogeneous slurries (Shah and Lord, 1991). This classification provides an indication of the distribution of solid particles over the pipe cross section under flow conditions. Homogeneous mixtures are those in which the distribution of solid particles is uniform over the pipe cross section. Suspensions of fine solid particles, where the two phases do not separate to any significant extent during flow, tend to be reasonably homogeneous and are usually treated as such. Although a homogeneous solid-liquid suspension is essentially made up of two distinct phases, there are situations in which particular slurries can be described satisfactorily by single-phase models. Heterogeneous slurry flow, on the other hand, applies to slurries of usually coarse particles where the two phases behave distinctly with a pronounced particle concentration gradient which is a result of particle settling under the influence of gravity. The study of such slurries is therefore more complicated since the single-phase flow approximation is not applicable to such essentially heterogeneous flows.

Although the homogeneous and heterogeneous flow regimes seem distinct, the transition from one regime to the other is not clear cut, and there are flow situations which have some of the characteristics of each regime. For example, food particulates usually have densities close to that of the carrier fluid, resulting in little or no tendency for settling under gravity, a characteristic of homogeneous flows. On the other hand, in the presence of coarse solid particles common in food suspensions, the two phases behave distinctly and the mixture is considered heterogeneous. An intermediate flow has been reported to occur when conditions for homogeneous and heterogeneous flow exist simultaneously (Legrand *et al*., 2007).

The main distinction between homogeneous and heterogeneous flow lies in the distribution of solid particles in the pipe cross-section. Until recently, no quantitative criterion has been available in the literature to describe particle distribution. The criteria usually used to delineate different flow regimes are generally subjective. Legrand *et al*. (2007) used a method based on flow visualization in order to characterize food suspensions with quantitative criteria by measuring the cumulative distribution of particles. The authors used large food particles with densities of 1048 and 1116 kg m^{-3} at concentrations up to 26% w/w.

A major factor which influences the flow behavior of solid-liquid mixtures is the rheological properties of the carrier fluid. In many situations, viscous Newtonian or non-Newtonian fluids are used as the carrier media. These carrier fluids 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; 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).

In practical situations, the transport of particulate matter can occur with a wide size distribution (e.g. coal dust to large lumps); in this case the fine colloidal particles tend to form a pseudo homogeneous shear thinning medium of enhanced apparent viscosity and density in which the coarse particles are conveyed. On the other hand, the heavy medium may consist of fine particles of a different solid, particularly one of higher density such as in the transport of overburden or cuttings in drilling muds. In such cases, the liquid vehicle usually behaves as a Bingham plastic whose yield stress and plastic viscosity increase as the solids concentration increases (Maciejewski *et al.*, 1997). The use (optional or otherwise) of non-Newtonian carrier fluids for processes which involve conveying of slurries through pipes, pipelines, or channels has been restricted by a lack of understanding of the behavior of these flows.

The vast majority of the documented data on solid-liquid flow relate to water-based slurries of fine particles. The flow of particles in non-Newtonian fluids has only been reported in a few studies. Charles and Charles (1971) transported fine sand particles in shear thinning clay suspensions. The head loss was six times smaller compared to that incurred using water as the carrier fluid. Similarly, Ghosh and Shook (1990) reported a reduction in pressure gradient for the flow of fine sand particles in a shear thinning CMC solution, but not for larger 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, and 1986) conveyed coal particles (up to 19 mm) in a slurry of fine coal which behaved as a Bingham plastic.

Solid-Liquid Velocity Profiles of Horizontal flow

Altobelli *et al*. (1991) →The solid particles, which were made of plastic, had a diameter of 0.76 mm and density of 1030 kgm^{-3}, and the carrier fluid was Newtonian viscous oil with a density of 875 kg m^{-3}. particle concentrations up to 39% v/v.→ Nuclear Magnetic Resonance (NMR) imaging techniques. Experiments were conducted for mean fluid velocities in the range 1.7-22.3 cm s^{-1}.→ It was found that for particle concentrations up to 10% v/v the ratio of the centre line velocity to the mean mixture velocity exceeded 2.0, but decreased monotonically at higher concentrations.

Ding *et al*. (1993)→Numerical simulation→ Numerical analysis, using a computer programme (COMMIX M), of the solid-liquid systems investigated by Altobelli *et al*. (1991).→ The numerical predictions of the fluid velocity were inclose agreement with the experimental data. The authors concluded that further developments in the multiphase solid-liquid model used would lead to increased confidence in the capability of the model in simulating dense slurry flow systems, and that such developments would result from comparisons with a wide data base of experimental results.

Fregert (1995)→ Suspensions of nearly neutrally buoyant particles in Newtonian carrier fluids in a 45 mm diameter pipe. The suspensions were fairly dilute with particle concentrations up to 10%, and the particle to- pipe diameter ratio ranged from 0.10 to 0.16.→ Experimental investigation → Conclude that (i) the maximum particle velocity occurred 4-6 mm above the pipe centre line, (ii) particle velocity was always smaller than the liquid velocity, and (iii) liquid velocity was generally slightly higher than that of the carrier fluid flowing alone.

McCarthy *et al*. (1997)→ The pipe had a diameter of 26.2 mm, and the solid particles were alginate spheres of 2.5 mm and 5.0 mm diameters. The particles were suspended at concentrations of 10%, 20%, and 30% w/w in a 0.5% w/w carboxy-methyl cellulose (CMC) carrier fluid whose rheology was best described by a power law model. The average flow velocity ranged between 2-35 cm s^{-1}.→ Nuclear

Magnetic Resonance (NMR) imaging techniques.→ The authors described the solid-liquid suspension with a power law model by measuring the degree of bluntness in the solid-liquid velocity profile and then calculating the corresponding flow behavior index which would result in the same degree of bluntness in single-phase flow. For the CMC solution flowing alone, the velocity profile, normalized using the mean flow velocity, showed increased bluntness as the flow rate was increased. For solid-liquid suspensions, the bluntness in the velocity profile was found to increase with particle concentration. The degree of bluntness was measured using the ratio of the flow behavior index of the CMC carrier fluid flowing alone to that of the solid-liquid suspension. This ratio was found to reach 0.38 at 30% w/w solids.

Le Guer *et al*. (2003)→ Suspensions of buoyant non spherical particles (few millimeters in dimensions) in water, intended to mimic the flow behavior of ice water mixtures. Particle concentrations up to 20% w/w were investigated.→ Ultrasound Doppler Velocimetry (UDV) The basic principle employed in UDV is the measurement of the time lapse between the transmission of ultrasonic bursts and reception of echoes from the flowing particles, thus allowing the measurement of the position of the particles. Flow patterns were determined by visualization of the flow mixture.→ Two flow patterns were observed: flow with a stationary bed at low flow velocities, with particles rising to the top of the pipe and forming a stationary bed; and flow with a moving bed. Due to the formation of these beds of particles, the velocity profile of the mixture was found to be significantly deformed compared with the velocity profile of water flowing alone. The deformation of the velocity profile increased with particle concentration.

Fairhurst *et al*. (2001) and Barigou *et al*. (2003) used the technique of Positron Emission Particle Tracking (PEPT) to determine the trajectories and velocity profile of coarse nearly-neutrally buoyant particles in non-Newtonian CMC carrier fluids. The solid particles used as model food particles were calcium alginate spheres of 5 and 10 mm diameters and 1020 kg m^{-3} density. Experiments were carried out at particle concentrations of 21 ± 2%, 30 ± 2% and 40 ± 2% v/v and mixture velocities ranging from 24 to 125 mm s^{-1}. The non-Newtonian carrier fluids employed were 0.3%, 0.5%, and 0.8% w/w CMC solutions the rheology of which was characterized by an Ellis model. A gravity-driven flow loop was used wherein the solid-liquid mixture flowed through a down pipe followed by a horizontal pipe, each of 1400 mm length and 45 mm inner diameter.

The authors identified two flow situations: concentric flow and capsule flow. The concentric flow pattern, observed at moderately high particle concentrations (e.g. 30% v/v), was characterized by a slow moving annulus close to the pipe wall and a faster moving central region. In the annular region, the effect of particle settling due to gravity was observed. At the base of the pipe, particles travelled at lower velocities than those at the top of the pipe. Except at the base of the pipe, particles travelled at velocities greater than the mean mixture velocity. At a higher particle concentration (40% v/v), and as particles were confined in a space that was insufficient to accommodate the spatial configuration of concentric flow, particles formed agglomerates, thus leading to capsule flow.

Two types of solid phase velocity profile were measured: global velocity profile and top to bottom velocity profile. The global velocity profile was measured by dividing the pipe cross section into four concentric regions and calculating the mean axial velocity of particles in each region. The top to bottom profile was measured by dividing the pipe cross section into eight sections, four above and four below the pipe centre line, and then calculating the mean velocity in each section as a function of radial position. Global solid phase velocity profiles showed considerable flattening compared with the theoretical single-phase carrier fluid profile and were symmetrical about the pipe centre line. Such profiles showed significant deviations from the actual velocities of the solid particles, particularly near the pipe wall, since the global velocity profiles do not take account of the asymmetric flow of the particles due to particle settling. Top to bottom velocity profiles, on the other hand, were found to be generally asymmetrical around the pipe centre line since they do take into account the asymmetric nature of the flow. Such profiles were, therefore, more representative of the actual particle velocities. Particles near the top of the pipe cross-section travelled at axial velocities significantly higher than those at the base of the pipe.

The degree of asymmetry in the top to bottom velocity profile, measured using a 'skewness parameter', was found to depend on the particle size and concentration, mean mixture velocity and carrier fluid viscosity. Asymmetry was strongly evident at the lowest particle concentration used (21% v/v) due to particle settling, with the position of the fastest flowing particles shifted ~2.5 mm above the centre line; while at higher particle concentrations velocity profiles were more symmetrical as particle settling was limited. The skewness of the solid phase velocity profile for 5 mm particles was found to be higher than that for 10 mm particles. It was also found that increasing the apparent viscosity of the carrier fluid reduced the skewness of the solid phase velocity profile.

Conclusion

A vast range of fluids of complex structures are now used in manufacturing an increasing number of products in a wide spectrum of industries including food, polymer, pharmaceutical, and chemical industries, in addition to applications in the oil, mining, construction, water treatment and power generation industries. Non-Newtonian fluids have received significant attention from researchers over the past decades due to their increasing importance in industry. This is reflected in the growing volume of research dealing with the structure, properties and flow behaviour of such fluids. Nonetheless, this area of research is vast and growing, and further studies into the behaviour of non-Newtonian fluids in complex flow situations are still needed.

A number of experimental techniques have been used in studying non-Newtonian flows, such as Laser Doppler Velocimetry (LDV), Particle Imaging Velocimetry (PIV), Nuclear Magnetic Resonance Imaging (NMR) and Positron Emission Particle Tracking (PEPT), but its application in this area has so far been limited.

While the measurement of solid and liquid phase velocity profiles in industrial solid-liquid mixtures is usually difficult. Computational Fluid Dynamics (CFD) is a useful tool for studying non-Newtonian flows. The CFD-predicted solid-phase velocity profiles were successfully validated using experimental PEPT measurements, whilst the computed solid–liquid pressure drop was validated using correlations from the literature (Eesa, M. & Barigou, M., 2009).

Whilst a thorough validation of CFD would require more extensive experimental data on pressure drop, which are presently unavailable in the literature, the study conducted by Eesa, M. & Barigou, M. (2009) has shown that, overall, CFD is capable of giving predictions which are no worse but probably more reliable than the correlations available in the literature as it is based on a full solution of the flow field. In this paper, it is shown that CFD have lot of potential to deal with non-newtonian fluid flow behaviour and pressure drop during the flow is concern.

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