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Optical measurement and numerical analysis of mono- and bidisperse coarse suspensions in vertical axisymmetric sudden-expansion

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ABSTRACT

A variant of the particle image velocimetry (PIV) in combination with the particle tracking velocimetry (PTV) technique is presented for measuring the velocity and concentration profiles of mono- and bidisperse semi-dilute suspensions (up to 4% volume concentration). An object recognition algorithm was applied to locate particles of each species in the plane of the laser light sheet. These data were then processed to obtain particle probability distributions and particle velocities. Unexpected preferential positions were observed in several experiments. Average slip velocities were extracted and converted into drag coefficients. The same were compared with drag coefficients predicted by state of the art correlations, considering sphericity and concentration. Experiments showed evidences of momentum transfer between species. Numerical analysis was performed with the two-fluid method considering monodisperse suspension to explain the cause of preferential positions found in the experiments.

Introduction

Bounded liquid–solid flows are widely found in industrial applications. The precise understanding of these flows is crucial in processes such as hydraulic conveying or drill cuttings transportation. For the assessment and optimization of operation conditions of such systems reliable information regarding the solid holdup, the residence time and the clogging potential,among others, are required. These in turn depend on the rheology of the liquid, the properties of the disperse particles, such as shape, density, size-distribution, and geometrical details of the pipe system.

While computational fluid dynamics (CFD) is commonly used in the solution of single phase flow problems for industrial applications and natural systems, this is still not the case in multiphase flows. A major obstacle towards the use of these methods for multiphase flows is the various constitutive relations, mostly empirical, necessary to describe the interactions between phases. In the case of liquid–solid flows, these are usually chosen depending on concentration. For dilute suspensions ($C < 0.001$) the momentum transfer between phases is unidirectional from the continuous phase to the dispersed phase. For semi-dilute suspensions ($0.001 < C < 0.05$) the dispersed phase influences the continuous phase and momentum transfer in both directions needs to be considered. Finally, dense suspensions may be further classified as collision dominated or contact dominated and the necessary models need to consider the corresponding relevant mechanical interactions.

In the case of multiphase flows, constitutive equations are obtained through experimental work. However, in physical experiments it is difficult to conduct wide parameter variations. Furthermore, it is usually not possible to obtain all quantities required to support empirical models simultaneously. With increasing computational power, the use of high resolution simulations emerges as an alternative approach to physical experiments and may be considered as a virtual (or computational) experiment (see also Hill et al., 2001; Hill et al., 2001; Beetstra, 2005; Van der Hoef et al., 2005; Yin and Sundaresan, 2008; Hölzer and Sommerfeld, 2009; Eskin and Derksen, 2010). However, due to limitations of computational resources and mathematical methods, this is still in its infancy. Therefore, only detailed physical experiments focusing on the phenomena of interest are able to validate the correctness of the assumptions made in the models.

Since the pioneering work by Segré and Silberberg (1961), who described the migration of particles up to a certain equilibrium position, also known as the tubular pinch effect, several analytical, computational and experimental analysis have been carried out to uncover the underlying physics of these phenomena (see also Saffman, 1965; Jeffrey and Pearson, 1965; Vasseur and Cox, 1976; Aoki et al., 1979; Dandy and Dwyer, 1990; Hogg, 1994;

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Patankar et al., 2001; Matas et al., 2004; Yang et al., 2005; Shao et al., 2008). As stated in previous works, they are due to lift forces induced by the shear as well as by the interaction of the wall with the flow disturbances induced by the particles and the shear (Takemura and Magnaudet, 2009). However, open questions still exist in the accurate quantification of these forces in more complex flows, for example in case multiple particles or poly-dispersity should be considered. The lift force acting on a particle in a swarm of other particles is believed to be dependent on the volume fraction. Choi and Joseph (2001) and Patankar et al. (2001), among others, have proposed to relate the lift force acting on single particles to the one acting on a particle within a swarm of other particles through correction functions similar to the ones proposed by Richardson and Zaki (1954) for drag forces. To develop such correlations a better understanding of these effects is needed.

With regard to polydisperse suspensions, most of the investigations focused on the settling velocities either by investigating single particles or the bulk sedimentation. Several authors (Mirza and Richardson, 1979; Masliyah, 1979; Selim et al., 1983; Patwardhan and Tien, 1985) proposed ad hoc modifications of the hindered settling function by Richardson and Zaki (1954) to account for the effects of the different species. Batchelor (1982) and Batchelor and Wen (1982) provided first descriptions of the hydrodynamic interaction between particles of different species at low Reynolds numbers. Due to the difficulties involved in the setting of physical experiments and analytical solutions, more recent works have used fully resolved numerical methods to generate computationally generated constitutive equations (Hill et al., 2001; Hill et al., 2001; Beetstra, 2005; Van der Hoef et al., 2005; Yin and Sundaresan, 2008). However, in flowing suspensions other forces than drag and gravity modify the microstructure of the suspension, i.e. lift forces, and affect the particle distributions and its locally averaged velocities. Therefore, dynamic simulations have also been shown to be necessary to study phenomena found in freely evolving suspensions (see also Yin and Sundaresan, 2008).

This paper consists of an experimental and a numerical part. First, experimental results are presented for mono- and bidisperse suspensions flowing through a vertical axisymmetric sudden-expansion at laminar regimes. The experiments were performed in a vertical flow loop, where fluid velocities and particle velocities and distributions could be measured by the application of non-intrusive methods. The measurements were conducted for different suspension flow rates with finite pipe Reynolds numbers of $O(100)$ and Stokes numbers of $O(1)$, several semi-dilute particle concentrations, up to 4%, and diverse bidisperse system configurations. The flow of suspensions through sudden-expansions creates transient phenomena, which were used to study two fundamental problems: lift forces acting on multiple particles and the momentum transfer between particles of different size. Lift forces on multiple particles are indirectly evaluated through particle distributions measured at a fixed position downstream of the sudden-expansion. Momentum transfer between species was evaluated through locally averaged slip velocities at the same position.

The second part of this work presents the numerical results of two-fluid method simulations, in which the Saffman–Mei lift model (Mei, 1992) was included. The numerical technique was used to analyse unexpected concentration peaks located at fluid velocity gradient transitions.

The reminder of this paper is organized as follows: the experimental PIV/PTV setup and the methods used to quantify particle distribution and velocities are presented in Section 'Experimental technique'; experimental results are shown in Section 'Experimental results'; in Section 'Numerical technique' we review the two-fluids model and the Saffman–Mei lift force model (Mei, 1992), which we use to calculate entrance lengths and particle distributions of systems similar to the experimental ones. In Section 'Numerical results and discussion' we comment the numerical results and use them to support conclusions drawn from the physical experiments. We finish with the conclusion in Section 'Conclusions'.

Experimental technique

Experimental setup

The experiments were carried out in the Vertical Multiphase Flow Loop at the Institute of Applied Mechanics of Clausthal University, shown schematically in Fig. 1. The construction followed concepts presented by Kriegel and Brauer (1966). Particles (glass spheres) are added to the flow through a feeding device (eductor) and transported through the hoses and later through the test section to a separating container. In this container, particles are redirected to the feeding device while the fluid (light liquid paraffin) enters a multi stage pump (16 stages, nominal flow rate $0.0016\,\mathrm{l\,s^{-1}}$). The experimental test section consisting of a Plexiglas® pipe has inner dimensions of Ø 64 × 2000 mm, which allows pipe Reynolds numbers up to 300. The entrance of the pipe has inner dimensions of Ø 28 mm, resulting in an expansion coefficient $\alpha = 2.28$. A sketch of the sudden-expansion geometry is shown in Fig. 2.

Due to its convenient refractive index (1.473 at 20 °C) light liquid paraffin (Shell Ondina 927) was selected as the working fluid. This fluid was selected to match the refractive index of the borosilicate particles ($n = 1.464$). According to a previous study conducted at our institute, the refractive index of Shell Ondina 927 at 30 °C (operating temperature) was 1.47. The slight difference produced clear delimitation of the particles, which was helpful for the particle location algorithm (CircularHough_Grd by Peng, 2010). Plexiglass was selected because of its resistance properties. The flow loop was conceived to measure suspensions with different carrying media (Newtonian, pseudoplastic and yield-pseudoplastic). Therefore, an easy to handle material to perform cleaning operations was favored. Although Plexiglass has a refractive index of 1.49, preliminary tests with single phase flows of Ondina 927 proved adequacy of the optical system. Strictly speaking, the walls of the pipe could be seen in the images, but reflections did not affect optical access to regions close to the walls. As shown in Fig. 4, the use of this fluid allows good matching of the refractive indexes with very little reflections or disturbances of the optical setup at the right wall of the pipe and virtually none at the left wall. The temperature was measured electronically in order to control density and viscosity. Density at 15 °C is $865\,\mathrm{kg\,m^{-3}}$ and the volumetric expansion coefficient is $\beta = 7.64 \times 10^{-4}$. The dynamic viscosity is correlated with temperature T within the range 20–40 °C using the following expression $\eta = -2.15T + 114.30\,\mathrm{mPa\,s}$. The dispersed phase consists of solid glass beads (Type P and Type S, from Sigmund Lindner GmbH) with diameters between 2 and 6 mm. Particle size distributions (PSD) obtained with the QICPIC-System developed by Sympatec GmbH are shown in Fig. 3. Densities of the glass beads are $2230\,\mathrm{kg\,m^{-3}}$ for borosilicate and $2580\,\mathrm{kg\,m^{-3}}$ for soda lime. Fluid and particle properties are reported in Table 1. The particles were continuously added to the fluid at different concentrations with the particle injection system. Upstream of the pump, the particles were separated using a filter to avoid damage of the pump and of the particles. The use of transparent spherical glass particles allowed avoiding interferences from particles situated in front of the laser light sheet.

Measurements of suspending liquid

To obtain two dimensional-two components (2D2C) suspending fluid velocity fields, the PIV technique was used. The working