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The effects of fluid viscoelasticity on the settling behaviour of horizontally aligned spheres

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ABSTRACT

A study on the interaction of particles settling in non-Newtonian fluids of shear-thinning, thixotropic and viscoelastic characteristics has been conducted. Key aspects of the rheological characteristics of the fluids that influence the interaction of the particles were examined by analysing the trajectories of two particles that are initially placed side-by-side in the fluid medium.

The interaction of the particles was found to be highly dependent on the separation distance that is initially set between them. If the initial distance is smaller than a critical value, the spheres would tend to attract and converge. In cases where the initial distance is greater than this critical value, the two spheres would tend to diverge, resulting in a slight ($\sim$20%) increase in their separation distance over their course of settling. This tendency to diverge was found to diminish as the initial distance is increased further from the critical value.

The magnitude of the critical separation distance was found to be primarily dependent on the normal stresses of the fluids. A correlation was thus proposed based on this observation. In cases where the two spheres do attract and converge, it was found that the spheres tend to follow a non-symmetrical trajectory, where one of the spheres possesses a slightly lower settling velocity than the other. As a result, the spheres appear to re-arrange themselves into a vertically aligned configuration. Once aligned, the shear-thinning and thixotropic characteristics of the fluid causes the lagging sphere to accelerate and collide with the leading sphere.

1. Introduction

A study on the settling behaviour of spheres in viscous non-Newtonian fluids holds high relevance in many industrial applications. In particular, the settling behaviour of particles in fluids with thixotropic and yield stress characteristics is of interest, due to the fact that many slurries and suspensions encountered in the industry tend to possess these types of fluid flow behaviour. The effects of these flow properties on the settling behaviour of a single particle have been examined on numerous occasions, notably by Valentik and Whitmore (1965), duPlessis and Ansley (1967) and more recently by Wilson et al. (2003, 2004), whereas many more have been reviewed by Chhabra (2007). Meanwhile, our knowledge on the interaction of particles in these types of fluid is still relatively limited. In several studies, it has been reported that the interaction between particles in some sheared viscoelastic suspensions causes the particles to aggregate, resulting in the formation of particle-rich and particle-depleted regions (Allen and Uhlherr, 1989; Phillips and Talini, 2007). The resulting irregular distribution of particles could potentially cause significant alterations in the rheological characteristics of the slurry/suspension, as well as severely impinge the efficiency of various unit processes involving these suspensions. This study is therefore important for the effective strategic formulation of the design and optimisation of unit processes involving suspensions, slurries and other viscous materials.

The current study has been preceded by several others (Gumulya, 2010; Gumulya et al., 2011), in which the settling behaviour of two particles along the same flow path in thixotropic and yield stress fluids has been examined. In these papers, Gumulya et al. found that a sphere that follows the flow path of another sphere tends to possess a higher velocity than the first/preceding sphere. The higher velocity of the second sphere causes it to 'catch-up' to the preceding sphere, resulting in a collision between the two. After this collision, it was observed that the two spheres tend to combine and aggregate. This tendency of two vertically aligned spheres to form an aggregate has been

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attributed towards the shear thinning and thixotropic properties of the fluid (Gumulya, 2010; Gumulya et al., 2011).

A study on the interaction of particles falling in viscous and viscoelastic fluids has previously been conducted by Joseph et al. (1994). Through a series of comprehensive experiments in various fluids, the authors found that the tendencies of particles to interact and aggregate is highly dependent on the ratio of first normal stress difference (N_1) with the shear stress due to the movement of the particles (τ). In addition, it was also noted that the formation of 'corridors' of reduced viscosity in some thixotropic fluids can contribute greatly towards the severity of this phenomenon. These hypotheses were supported by Gheissary and van den Brule (1996), as well as several researchers who examined the formation of particulate lines/chains in sheared suspensions and viscous fluids (Phillips and Talini, 2007; Scirocco et al., 2004; Won and Kim, 2004). Scirocco et al. (2004) have suggested that the alignment of spheres in sheared suspensions is highly dependent on the ratio of N_1 with τ. Phillips and Talini (2007), meanwhile, suggested a similar hypothesis, based on the results of their multipole expansion approach, which incorporates the contributions of the viscoelastic stresses of the fluids in the region around the moving particles. This view was later supported by Won and Kim (2004), who further hypothesised that the formation string-like structure is caused by the shear thinning properties of the fluid.

Numerical studies on the interaction of particles settling at low Reynolds numbers ($\mathrm{Re} \ll 1$) in second-order fluids have previously been conducted by Phillips (1996) and Ardekani et al. (2008). While the results of these studies mostly agree with the experimental observations listed above, neither Phillips (1996) nor Ardekani et al. (2008) observe any instances of critical separation distance, above which the particles would tend to diverge and repel each other. This parameter of critical separation distance was suggested by Joseph et al. (1994), upon their examination on the interaction of side-by-side particles settling from several different values of initial separation distance. More recently, Khair and Squires (2010) presented a numerical study, computing the forces experienced by a pair of probes as they are moved through a second-order fluid at low Reynolds numbers ($\mathrm{Re} \ll 1$). Through this study, it was suggested that the interactive nature of the side-by-side probes, i.e. whether it is attractive or repulsive, is not dependent on their separation distance, but rather on the magnitude of the first and second normal stresses of the fluid.

In this paper, the roles of inertia, viscosity, and normal stresses on the interaction of two side-by-side spheres settling in viscoelastic fluids will be examined. The movement of the two spheres (initially separated by a set distance of 25–50 mm) will be monitored through photogrammetric methods. The particle Reynolds number for the experiments (see Eq. (9)) ranges from moderate to high ($0.1 < \mathrm{Re} < 10$), thus allowing for the effects of fluid inertia on the interaction of the particles to be examined. The results of this experiment will be compared with the observations made by Joseph et al. (1994), who conducted their measurements at low to moderate Re values ($0.001 < \mathrm{Re} < 0.5$), as well as those by the researchers mentioned above. In conducting this study, it is hoped that factors that affect the interactive behaviour of particles settling in viscous fluids can be further identified and characterised.

2. Experimental method

The experiments were conducted in dilute solutions of polyacrylamide (MAGNAFLOC 5250L, supplied by BASF Australia Ltd, Kwinana, WA), which are commonly used as the suspending media in industrial slurries. These solutions are clear and transparent, and as a result, the motion of spherical particles through the fluids can be observed through an optical sensor system (Lichti et al., 2009).

The settling experiment is executed in a straight-walled column made of clear Perspex sheets, with square cross section and closed bottom. The dimensions of the column ($0.2\ \mathrm{m} \times 0.2\ \mathrm{m} \times 1.2\ \mathrm{m}$) have been selected based on the rheology of the test fluids, such that two metal spheres (S.G. = 7.64–8.88, D = 6.35–10 mm) that are initially side-by-side with a maximum separation distance of 50 mm can fall through the fluids without experiencing significant wall effects (Mena et al., 1987; Chhabra and Uhlherr, 1998).

A ball dropping device is located at the centre of the upper enclosing cover of the column. This device was designed such that two spheres can be released simultaneously, with a specified gap between the two spheres (25–50 mm), into the solution without any rotational movement or initial velocity (Gumulya, 2010). Three different sphere materials (bronze, chrome-plated steel and stainless steel) with different diameters (6.35, 7.95 and 9.95 mm) were used during the experiments. The experiments were conducted in a laboratory with a controlled temperature of 23.5 (± 1) °C. Throughout the experiments, a standardised 'resting' time of 15 min between each experiment was established, to allow the fluid solution to reconstitute itself and to regain ~95% of its original viscous properties (Horsley et al., 2004).

The optical sensor system comprises of two synchronised video cameras. Commercially available software was used to control the image acquisition process, as well as for the measurement and tracking of the progression of spheres in the two dimensional imagery. Custom-built software was then developed to analyse the acquired data through photogrammetric methods. The performance of this system was extensively examined by Lichti et al. (2009), and it was demonstrated that this sensor system is able to achieve precision and accuracy levels of greater than 1 mm in coordinate measurement.

The rheology of the Magnafloc solutions was examined using a rheometer from HAAKE (Thermo Electron Corporation, Karlsruhe, Germany), HAAKE MARS II. The cone-and-plate geometry (C35/4Ti from Thermo Electron Corporation, Karlsruhe, Germany) was used at a standardised temperature of 23.5 °C. The diameter of the cone was 35.007 mm with an angle of 3.99°. The tip of the cone was truncated and a gap of 0.139 mm with the metal plate was automatically set before each measurement.

3. Fluid rheology

Fig. 1 shows the rheograms of the fluids under steady-state conditions. It can be seen in this graph that all three fluids exhibit very high values of viscosity at low rates of shear. These fluids are also strongly shear-thinning, as indicated by the sharp decrease in the slopes of the rheograms with increasing values of shear rate. Within the range of the rheological measurement, the apparent viscosity of these fluids varies from 0.2 Pa s to over 110 Pa s.

Gumulya (2010) has examined the rheological properties of the solutions under both steady and transient conditions, and found that the shear viscosity of the fluids can be modelled closely with a mathematical model that incorporates a scalar parameter (λ) that represents the 'local degree of interconnection' in the fluid. Within the context of this study, it is presumed that this interconnection is caused by the existence of hydrogen bonding between polyacrylamide and water molecules in the aqueous acrylamide solutions (Gumulya, 2010). The value of λ varies between 0 and 1, with 1 representing a fluid medium with a fully intact structure (i.e. undisturbed). Conversely, a λ value of 0 represents of a fluid medium whose internal structure has been completely destroyed/sheared. The dependence of the apparent