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Settling of spherical particles in unbounded and confined surfactant-based shear thinning viscoelastic fluids: An experimental study

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HIGHLIGHTS

- ▸ Settling velocities of spheres in shear thinning viscoelastic fluids are measured.
- ▸ Drag reduction at lower Weissenberg numbers (We) is observed.
- ▸ This is followed by a transition to drag increase at higher We.
- ▸ Elasticity is observed to reduce the effect of confining parallel walls.
- ▸ New correlations to quantify settling velocities are presented.

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ABSTRACT

An experimental study is performed to understand and quantify settling velocity of spherical particles in unbounded and confined surfactant-based shear thinning viscoelastic fluids. Experimental data is presented to show that elastic effects can increase or decrease the settling velocity of particles, even in the creeping flow regime. Experimental data shows that a significant drag reduction occurs with increase in Weissenberg number. This is followed by a transition to increasing drag at higher Weissenberg numbers. A new correlation is presented for the sphere settling velocity in unbounded viscoelastic fluids as a function of the fluid rheology and the proppant properties.

The wall factors for sphere settling velocities in viscoelastic fluids confined between solid parallel plates are calculated from experimental measurements made on these fluids over a range of Weissenberg numbers. Results indicate that elasticity reduces the effect of the confining walls and this reduction is more pronounced at higher ratios of the particle diameter to spacing between the walls. Shear thinning behavior of fluids is observed to reduce the retardation effect of the confining walls. A new empirical correlation for wall factors for spheres settling in a viscoelastic fluid confined between two parallel walls is presented.

1. Introduction and past work

The free settling velocity of particles suspended in liquids is of importance in a wide variety of industrial applications. Slurries of solids suspended in fluids are widely used in applications ranging from semi-conductor processing to pharmaceutical manufacturing. In the oil industry, viscoelastic fracturing fluids are used to suspend proppants (typically sand) in hydraulic fractures. The proppants keep the created fracture open upon cessation of pumping. Settling of proppants is governed by the properties of proppants, rheology and density of fluid and the retardation effect of confining fracture walls.

The settling velocity of single spherical particle in a Newtonian fluid in the creeping flow regime was first derived by Stokes in 1851, which is commonly referred to as the Stokes equation. Subsequent researchers studied settling at higher Reynolds numbers and presented expressions to calculate the drag force (Clift et al., 1978; Khan and Richardson, 1987; Zapryanov and Tabakova, 1999; Michaelides, 2002, 2003). The confining walls exert a retardation effect and reduce the settling velocities of particles. This effect is quantified in terms of a wall factor, F_w, which is defined as the ratio of the settling velocity in the presence of confining walls to the unbounded settling velocity in the same fluid. Faxen (1922) pointed out that for Newtonian fluids, in the creeping flow regime, the wall factor depends only on the ratio of the particle diameter to the slot width, irrespective

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of the viscosity of the fluid. Subsequently, many theoretical and experimental investigations determined the wall factors for spheres settling in different cross-section tubes over a wide range of Reynolds number (Bohlin, 1960; Clift et al., 1978; Miyamura et al., 1981; Tullock et al., 1992; Chhabra, 1996, 2002, 2007). In summary, there is an extensive and a coherent body of information available for the calculation of drag on spheres settling in Newtonian fluids. On the other hand, past work on the determination of settling velocity of particles in non-Newtonian fluids, particularly viscoelastic fluids, is not as complete.

1.1. Settling in unconfined viscoelastic fluids

Acharya et al. (1976, 1988) conducted experiments with shear-thinning viscoelastic fluids and concluded that in creeping flow regime, shear-thinning effects completely overshadow the viscoelastic effects and values of drag coefficient are in excellent agreement with the purely viscous theories (Chhabra and Uhlherr, 1980; Bush and Phan-Thien, 1984). However, other studies reported a drag reduction in the creeping flow regime (Broadbent and Mena, 1974; Sigli and Coutanceau, 1977). Acharya et al. (1976, 1988) also observed that at higher Reynolds numbers, the fluid elasticity causes the settling velocity to increase.

Chhabra et al. (1980) performed experiments in Boger fluids (constant viscosity elastic fluids) and observed a decrease in the drag coefficient with increasing values of Weissenberg number, till it reaches an asymptotic value at high Weissenberg numbers. The Weissenberg number is a dimensionless measure of the elastic effects, defined as follows:

$$\mathrm{We} = \frac{2\lambda V}{d_p} \quad (1)$$

where λ is the relaxation time of the fluid, V is the settling velocity in the fluid and d_p is the diameter of the spherical particle. Brule and Gheissary (1993) performed experiments with Boger fluids as well as shear-thinning viscoelastic fluids, and observed that the settling velocity was reduced due to the elastic effects in the fluid rather than increased as reported by Chhabra et al. (1980). Walters and Tanner (1992) summarized that for Boger fluids, elasticity causes drag reduction with increasing Weissenberg number which is followed by a drag increase at higher Weissenberg number. They also highlight the other important effects such as the velocity overshoot effect (Jones et al., 1994) and time effect (Bisgaard, 1983; Cho et al., 1984; Jones et al., 1994).

Through an extensive review of the past experimental and numerical work, McKinley (2002) concluded that the observed drag increase at high Weissenberg numbers is due to the extensional effects in the wake of the settling sphere. Later, Chhabra (2007) provided another comprehensive review of past work and highlighted the gap between the theory and experimental results. Most experimental studies pertain to conditions where viscosity is a function of the shear rate whereas most theoretical developments model the effect of fluid viscoelasticity on spheres in the absence of shear thinning effects. Incorporating a realistic description of shear rate dependent viscosity together with fluid viscoelasticity has been a real challenge in theoretical developments. In the absence of a complete constitutive solution one of the objectives of this work is to present an empirical relation that can quantify and capture the effect of both viscoelasticity and shear-thinning on particle settling in unbounded fluids.

1.2. Effect of confining walls on settling in non-Newtonian fluids

Machac and Lecjaks (1995) conducted experiments with purely viscous shear-thinning (power-law) fluids and showed that the wall retardation effect decreases with the decreasing power law index, n of the fluid. Missirlis et al. (2001) preformed finite-element and finite-volume simulations for purely-viscous shear-thinning fluids and showed that the drag coefficient converges to a constant value as the power law index approaches zero, independent of the sphere-to-tube diameter ratio. Song et al. (2009) numerically investigated the drag force on spheres in cylindrical tubes and reported that the wall effects were less severe in power law fluids than in Newtonian fluids (in the range: Reynolds number 1–100; power law index 0.2–1 and sphere-to-tube diameter ratio 0–0.5).

The determination of the wall factors for particles settling in viscoelastic fluids has been an area of ongoing activity over the past years. The key observations have been: (i) retardation effects due to the cylinder walls reduce with increasing levels of elasticity of the fluid (Chhabra et al., 1981), (ii) at a sphere-to-tube diameter ratio of 0.25, there is a considerable enhancement in drag with the increase in Weissenberg number but the drag enhancement disappears upon increasing the sphere-to-tube diameter ratio to 0.5 (Jones et al., 1994; Navez and Walters, 1996), (iii) numerical simulations suggest that for unbounded flows and flows with small blockage ratios (less than 0.1) the drag on the cylinder is increased by elasticity. On the other hand for flows with higher blockage ratios the trend is completely reversed (Huang and Feng, 1995) and (iv) increased shear-thinning effects reduce the drag (Sugeng and Tanner, 1986) and also reduce the retardation effect of the walls (Huang and Feng, 1995).

It is important to note that all the work done to determine the wall effects in viscoelastic fluids has been done for spheres settling in cylindrical tubes. No correlations/models are available to determine the wall factors for spheres settling in viscoelastic fluids between two parallel walls, which will be addressed in this work.

The objectives of this work are two-fold: (a) investigating the influence of visco-elasticity and shear-thinning simultaneously on settling velocities in unbounded fluids; (b) quantifying the retardation effect of the bounding parallel walls on settling velocities in shear-thinning viscoelastic fluids. This is done by performing particle settling experiments in fluids of varying viscosity, elasticity and degree of shear thinning. The particle Reynolds number in the experiments ranges from 5×10^{-4} to 2.63, thereby allowing the investigation of influence of elasticity on settling velocity, inside and outside the creeping flow regime.

2. Experimental methods

2.1. Description of the fluids

In this experimental study a polymer-free, viscoelastic, two-component, surfactant-based fluid system (Zhang, 2002; Gupta and Tudor, 2005) is used for performing the settling experiments. The fluid system has been widely used for hydraulic fracturing treatments in oil and gas wells in many producing fields and formations (Gupta et al., 2005). It consists of an anionic surfactant (such as sodium xylene sulfonate) as one component and a cationic surfactant (such as N,N,N, trimethyl-1-octadecamonium chloride) as the second component. The two components are diluted and mixed using an overhead mixer at high rpm to ensure proper mixing. When the two components are mixed at different concentrations and in different proportions the surfactant mixture forms worm like micelles that yield a variety of different rheological properties. This fluid system was chosen for our study because it is optically transparent and its rheology can be easily controlled by systematically varying the concentrations and proportions of the two components. Seven fluid mixtures of different concentrations labeled as Fluid 1 through 7 are used in