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Velocity Fields around Single and Interacting Particles Sinking in Mucus-rich Water

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Abstract

Exopolymers dispersed in water create mucus-rich environments that can modify sedimentation dynamics when secreted in excess by microorganisms. Here we use PIV measurements combined with shear and extensional rheology to demonstrate non-Newtonian effects of mucus-rich water including extended flow, negative wake, and aggregation of solid spheres in test solutions. The methodology designed in this study allows the future development of analogue experiments to model the sinking dynamics of microplastic pollutants and mineral grains and organic aggregates in algal bloom-afflicted regions or wastewater treatment plants.

1. INTRODUCTION

Natural waters gain non-Newtonian properties when exopolymers (EPS) are excessively secreted by algae and bacteria (Jenkinson 1986), which affects the sinking dynamics of particles, e.g., microplastics (Mrokowska and Krztoń-Maziopa 2024). However, the influence of mucus on the flow field around sinking particles remains elusive.

Aqueous solutions of polysaccharides, which dominate mucus as EPS display shear-thinning and viscoelastic properties. These non-Newtonian systems can induce distinct flow behaviour, such as forming extended or negative wakes behind sinking particles. Moreover, particles sinking on top of one another in shear-thinning thixotropic liquids may experience mutual attraction (Zenit and Feng 2018). Nevertheless, the specific effects of mucus-rich environments on particle dynamics are still unclear. The present study aims to identify velocity field patterns around particles sinking in such conditions. Here we used xanthan gum as a proxy for EPSs to address the flow field around solid spheres in mucus-rich aqueous environments.

2. MATERIALS AND METHODS

Two solutions of XG (Sigma Aldrich) in distilled water with concentrations of 0.75 gL^{-1} (XG 0.75) and 1.25 gL^{-1} (XG 1.25) were studied. The density of solutions, ρ_f, was measured using DMA 4100 M densimeter (Anton Paar), shear rheology with a Physica MCR 301 rheometer with coaxial cylinders measuring geometry (0.714 mm gap), and extensional rheology using Extensional Capillary Breakup Extensional Rheometer (CaBER, ThermoFisher). Three types of test spheres were made of POM (polyoxymethylene) – diameters, d = 5.00 mm (S1), and 4.00 mm (S2), density, ρ_p = 1.37 g cm^{-3}, and made of Si_3N_4, d = 2.38 mm (S3), ρ_p = 3.20 g cm^{-3}.

The test liquid in a transparent settling tank was seeded with fluorescent PMMA particles (1–20 μm). A vertical laser sheet (green light, Nd:YAG double-pulsed laser) was aligned with the trajectory of a falling sphere. Camera images (2448×2048 pixel, 124 Hz) were processed using Dantec Dynamic Studio and custom scripts in Matlab®. Adaptive PIV analysis was applied to compute instantaneous velocity vector fields. The average sinking velocity of spheres, U, was estimated from time-resolved particle position data derived from PIV images.

3. RESULTS

Test liquids demonstrated shear-thinning behaviour, with a power-law region corresponding to shear rates, $\dot{\gamma}$, typical for sinking test particles (32–200 s^{-1}) along with slight thixotropy (Fig. 1a). Moreover, the liquids showed stretching characterised by extensional viscosity (Fig. 1b), with the Trouton ratio (extensional viscosity, η_E (Fig. 1b) to shear viscosity, η (Fig. 1a)) for sinking particles ranging from 18 to 57. Both viscosities were higher for XG1.25 due to a more entangled network in the dispersion of larger polymer content.

The flow field around spheres sinking with modified Reynolds number ($\rho_f Ud/\eta$) between 9 and 80 displayed non-Newtonian characteristics (Fig. 2a). Velocity profiles in front of a sphere (Fig. 2b) were similar for the three test particles, with distances z/d = 3.5 for XG0.75 and 4.5

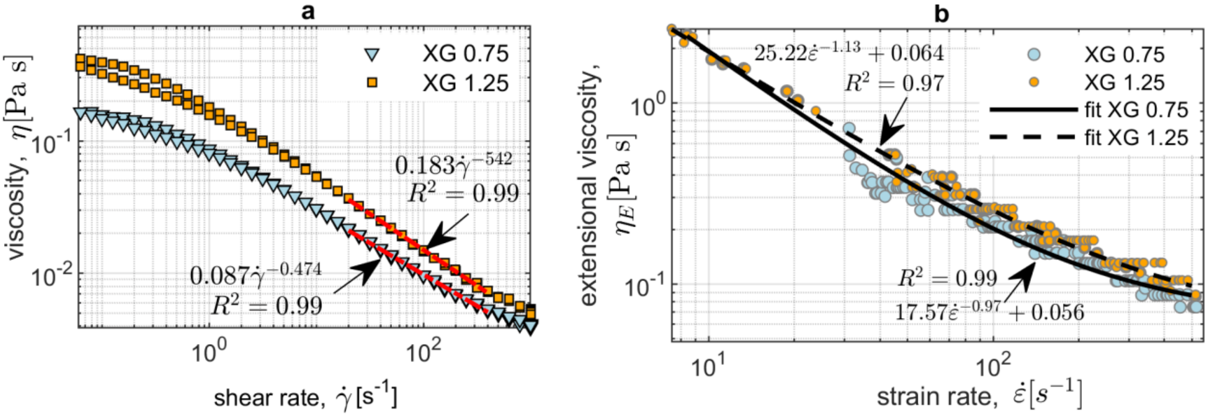

Fig. 1. Viscosities of xanthan-based liquids: a) shear viscosity curves with slight thixotropy and power-law fitted region indicated by red lines; b) extensional viscosity curves with power function fitting.

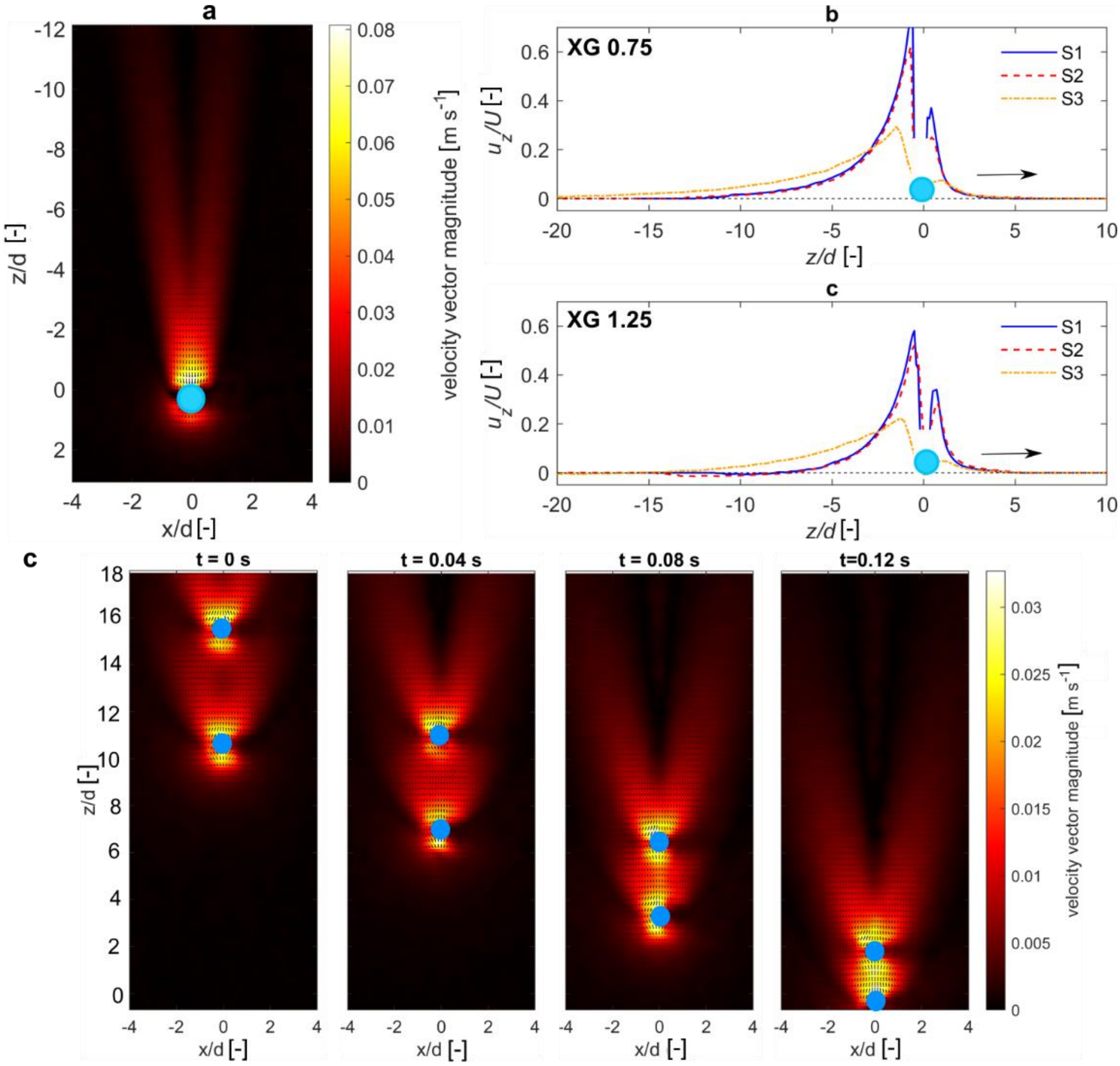

Fig. 2. Instantaneous velocity field around sinking spheres: a) S1 sinking in XG0.75; b) non-dimensional fluid velocity at the vertical centerline of spheres in XG0.75 and XG1.25, arrow indicates sinking direction; c) velocity fields around interacting spheres sinking in XG1.25 solution, negative wake visible.

for XG1.25. The greater extent in XG1.25 can be attributed to a more structured polymeric network. The wake's shape behind a sphere varied depending on the type of solution, showing a predominantly extended wake pattern, with the onset of negative wake in XG1.25. Figure 2b shows that stagnation points formed closer to S1 and S2 than for S3 particles (e.g., $z/d = 8$ for S1, S2, and $z/d = 15$ for S3 in XG1.25). This was accompanied by an increase in wake angles from 15° in XG0.75 to 22° in XG1.25 and from 10° to 14° for S1 and S3, respectively.

Figure 2c demonstrates that particles sinking in a doublet experienced attraction in the XG1.25 solution. This was caused by a time-dependent decrease in shear viscosity behind a leading particle evidenced by thixotropy in the viscosity curve (Fig. 1a).

4. CONCLUSIONS

Our experiments demonstrated that EPSs can induce non-Newtonian properties resulting in wake patterns affecting settling dynamics and particle interactions. This study highlights the significant role of exopolymer’s concentration and network structure on modulating particle dynamics.

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