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Creeping flow of a wormlike micelle solution past a falling sphere: Role of boundary conditions

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A B S T R A C T

Creeping flow of a wormlike micelle solution past a falling sphere with varying surface roughness is considered. A combination of particle tracking velocimetry, particle image velocimetry and microscopy is used to obtain detailed information on the flow of the wormlike micelle solution based on CTAB/NaSal (9 mM/9 mM) around the falling spheres. We find that the surface roughness strongly affects the dynamics of the sphere motion in wormlike micelles such that roughened spheres fall with higher terminal velocities than smooth spheres. In addition, for the roughened spheres the stagnation point is closer to the sphere center of mass, and the magnitude of the negative wake is stronger. We also report, for the first time, formation of micron-size air bubbles at the surface of roughened spheres that are responsible for these unusual results. When these microbubbles are removed, roughened spheres fall with similar velocities as smooth spheres. The latter result may be considered as indirect evidence for no-slip boundary conditions in this CTAB/NaSal system. This hypothesis is further validated with local velocity profile measurements for the wormlike micelle solution sheared in a custom built Taylor–Couette geometry.

1. Introduction and background

Wormlike micelle solutions have attracted considerable interest in the past decade due to their fundamental and industrial significance [1,2]. These systems are composed of simple constituents, usually surfactants, salts and water, yet exhibit interesting non-linear mechanical responses to the flow and remarkably simple linear responses [3]. Over certain ranges of temperature and concentration, the surfactants and salts may form self-assembled wormlike structures in aqueous solutions akin to flexible polymer solutions [1,2]. However, unlike polymer solutions, wormlike micelles break and reform under shear [4]. Wormlike micelle solutions have revealed a wealth of interesting fluid dynamics in shear and extensional flows [5–14]. In simple shear flow and within a range of shear rates, some wormlike micelle solutions exhibit shear banding. Shear banding in these systems is characterized by the formation, in a uniform shear flow, of co-existing regions that undergo different shear rates [5,7,8,15,16]. The mechanical signature of the shear banding phenomenon is commonly taken as the presence of a plateau in the flow curve [3,5,17]. The nature of such non-linear behaviors is still under active investigation from experimental and theoretical standpoints [18].

The role of solid-liquid boundary conditions in flow of wormlike micelle solutions has been extensively studied for a variety of wormlike micellar systems predominantly in shear flows [6,11,19–40]. To quantify the local behavior of the wormlike micellar systems near a solid wall, local velocity profiles have been measured by different techniques including Nuclear Magnetic Resonance (NMR) [23,25,26,30,32,37], Particle Tracking Velocimetry (PTV) [22,24,29,40], Particle Image Velocimetry (PIV) [6,19,27,34,36,39], Heterodyne Diffusive Light Scattering (HDLS) [35,38], and Ultrasonic Speckle Velocimetry (USV) [11,20,21,28,31,33]. Based on the available literature, some of the wormlike micellar systems exhibit wall-slip at the solid-liquid boundary [11,19–21,23–37,39]. The slip phenomenon is characterized by a mismatch between the velocity of the wormlike micelle solutions adjacent to the wall and the velocity of the wall itself. Conversely, there are other wormlike micellar systems that do not show any sign of wall-slip at the solid-liquid boundary in shear flows [6,22,38,40]. Therefore, it is still not clear why some wormlike micellar systems exhibit wall-slip while others do not.

Wormlike micelle solutions have also been the subject of a few studies in predominantly extensional flows [13,41–44]. Rothstein and co-workers, used a filament stretching extensional rheometer, and showed that beyond a critical stress the filament of the wormlike

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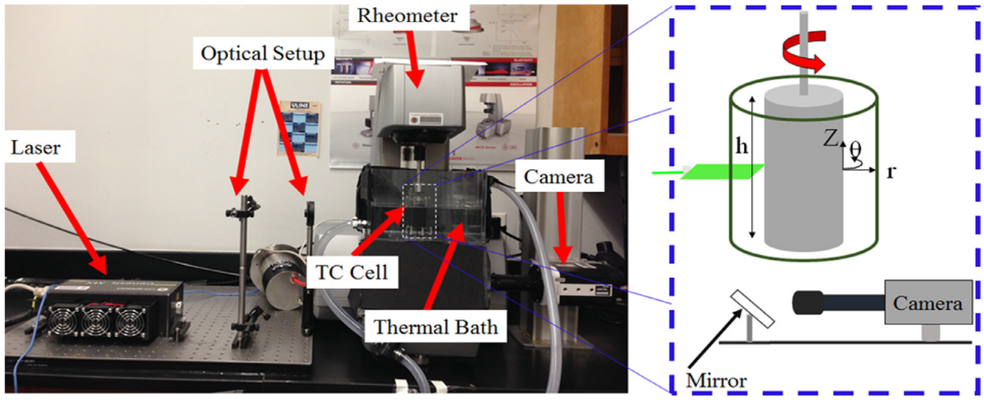

Fig. 1. The experimental setup with the custom built Taylor–Couette geometry for measuring the azimuthal velocity profile $V_\theta(r)$.

micelle solution undergoes a sudden rupture [13,42]. The sudden failure of the wormlike micellar filament is attributed to the wormlike micellar chain scission under extensional forces [13,42]. The tendency of the wormlike micelles to break under extensional flows has been linked to interesting phenomena such as instabilities in bubble rise or sphere sedimentation [12,14,41,45]. Recent experiments on flow of wormlike micellar solutions past a falling sphere showed that beyond certain thresholds, a falling sphere never reaches a constant terminal velocity. Instead it undergoes an instability that is characterized by sudden acceleration and deceleration in sphere velocity [12,41,45,46].

Although the role of boundary conditions has been reported for a wide range of shear banding wormlike micelle solutions in different flow geometries, the degree, if any, to which the boundary conditions affect the dynamics of the sphere sedimentation in wormlike micelles [12,41,45,46] is as yet unknown. The velocity of the sphere and the structure of the wake should in principle be affected by the type of the boundary condition at the sphere surface. In this paper, our main goal is to probe the role of the solid-liquid boundary conditions on the falling velocity of the sphere and also on the structure of the flow around a falling sphere in a model shear banding wormlike micelle solution based on CTAB/NaSal (9 mM/9 mM). The majority of the past sphere sedimentation experiments are carried out in a wormlike micelle solution based on CTAB/NaSal. However, to the best of our knowledge, those studies have only utilized spheres with smooth surfaces [12,41,45,46]. In this work we attempt to modify the sphere boundary conditions by considering spheres with smooth and roughened surfaces.

2. Experiments

2.1. Materials and methods

The semidilute wormlike micelle solution studied in this paper consists of CTAB/NaSal (9 mM/9 mM) dissolved in de-ionized water. This solution is selected for study since the majority of the sphere sedimentation experiments in wormlike micelle solutions have been conducted in a similar system [12,41,45]. CTAB and NaSal are purchased from Spectrum Chemicals and Sigma-Aldrich and used as received. The rheological properties of this solution were obtained using a commercial rheometer (model MCR 302, Anton-Paar Co.) in a concentric cylinder geometry with inner and outer radii of $R_1 = 13.35$ mm and $R_2 = 14.45$ mm, respectively. Rheological experiments are performed with both smooth and roughened inner cylinders. Roughened boundaries were obtained by sand blasting the inner cylinder.

Sphere sedimentation experiments were carried out in a vertical glass column with the inner radius $R = 4.25$ cm and height $L = 100$ cm. The vertical column was filled with the wormlike micelle solution and the temperature of the solution was maintained at T = 23 °C with a temperature controlled water bath. Three spheres including Nylon, Delrin and Teflon with different densities (1.14, 1.4 and 2.3 gr/cm^3, respectively) and radii ($a = 1.58$–3.17 mm) were used for these experiments. The surface of a sphere was modified with sand paper (model 3M, Grit 50). We confirmed that there is no measurable weight change due to the roughening process. In the experiments presented below and for each sphere type, we use a single roughened sphere. Spheres were released at the center of the cylindrical column using a drill chuck that is mounted on a translation stage. Sphere motion was monitored with a high speed camera (model Phantom Lab Miro-310, Vision Research Inc.). The high speed camera was coupled with a zoom 6000 Navitar lens and a 2X adapter. The combination of this lens and the camera allows us to resolve a 3 mm × 5 mm field of view with a capture rate of 1000 fps. Therefore, the velocity of a fluid element can be resolved down to 70 μm away from the sphere surface. To characterize the velocity of the fluid in the wake of the sphere, a 50 mm zoom lens (from Computar) was used. With the latter lens setup, the axial velocity was resolved up to a distance $\sim 35a$ away from the sphere center of mass in the wake of the sphere, where a is the radius of the sphere. More details on implementation of the PIV technique is provided in an earlier paper [12]. Additionally, the falling velocity of the spheres was measured by tracking the particle center of mass via a particle tracking plug-in in ImageJ [47].

We also note that the local azimuthal velocity profile $V_\theta(r)$ of the wormlike micelle solution is measured in a custom built Taylor–Couette (TC) cell. Fig. 1 shows the flow velocimetry setup and a schematic of the TC cell. The inner cylinder of the TC cell is made of Delrin with $R_i = 13.35$ mm and is connected to the rheometer. The stationary outer cylinder is precision-made borosilicate glass with $R_o = 14.53$ mm. The gap of the TC cell is $\varepsilon = R_o - R_i = 1.18$ mm and the height of the inner cylinder is $h = 50$ mm. This provides an aspect ratio of $\Gamma = h/\varepsilon = 42.3$, which renders end effects negligible. To control the temperature of the fluid, the TC cell is placed in a temperature controlled thermal bath. The wormlike micelle solution is seeded by 0.01 wt% microspheres (model 110PB provided by Potters Industries LLC) with density of 1.1 gr/cm^3 and a mean diameter of 25 μm. Additionally, a laser (model Genesis MX532-8000 from Coherent Inc.) was used to generate a sheet of light in the flow plane ($r - \theta$) of the TC cell. To visualize the flow plane we use a combination of the aforementioned high speed camera, a macro zoom lens (model VSZ-0745 from VS Technology) and a 0.5X front converter lens (model VSZ-0.5X from VS Technology). To measure the azimuthal component of the velocity, we track the center of mass of hundreds of microspheres via the particle tracking plug-in in ImageJ [47].

3. Results and discussion

3.1. Fluid characterization

Fig. 2(a) shows the flow curve of the CTAB/NaSal (9 mM/9 mM)

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