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Fluid dynamics of film drainage around solid particles and spheres falling through a liquid-liquid interface

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ABSTRACT

This paper reports on experimental studies of the passage of particles and spheres in two immiscible fluids. The interface between the two fluids is established by water, or by water based polymer solutions, and an overlying oil phase. The polymer solution is Poly Anionic Cellulose (PAC) dissolved in water to explore the effect of rheology. As the particles cross the interface oil still wets and surrounds the particle but is gradually drained by drag forces from the polymer solution. The drainage mechanism of the oil is of interest both from an engineering point of view and as a theoretical-numerical problem. Several mechanisms are present, including thin film drag and interface ripples on the film. Also the entrainment of the drained oil phase into the wake of the particle is of importance for the overall movement of the particles. The experiments were carried out using high-speed video imaging to obtain a detailed analysis of the interface drainage modes, as well as the movement and dynamics of the spheres. Both Particle Image Velocimetry (PIV) technique and Particle Shadow Velocimetry (PSV) are used for studying and measuring the flow around the particles.

INTRODUCTION

Different degree of sedimentation occurs through a vertical conduit during simultaneous flowing of fluids and solids. This phenomenon can be observed during well drilling and completion. The reason is that particles are added to drilling fluids to provide density. The function of the drilling fluids is to keep the solids in suspensions. The petroleum industry is struggling to meet the challenges when transporting cuttings out of the borehole. Omland[1] reported that due to the complexity of the drilling fluid which is related to sag settling models have not shown to be able to predict particle settling in drilling fluids well. Also, cement pastes and drilling fluids are typically suspensions of coarse particles in a fluid. Such a particle can settle out due to their densities compared to the suspending fluids. Although such systems involve a group of solids, the study of a single particle is the basis for further investigation.

The terminal velocity of solids is more suitable to be measured as this affects the hydrodynamics parameters such as drag coefficient, surface tension, variable sizes and buoyancy force. These are some of the most important parameters for the efficiency of drilling long deviated wells.

An important phenomenon in fluid dynamics and many industrial processes involves such changes at the interface between two immiscible fluids. This interface may deform and become diffuse. This situation is commonly referred to as emulsion which consists of droplets of one liquid phase dispersed in surrounding liquid phase.

BUCKLING INSTABILITY

If a particle is crossing an interface between oil and water, it will draw out a funnel shape interface behind the particle. The interface continues and a filament of the oil phase is growing. Eventually, the filament pinches off at a certain point. Fig. 1 shows an illustration of the impact of the particle on the water phase.

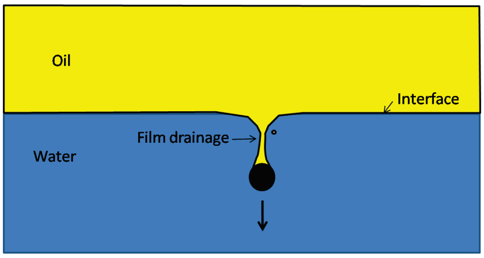

Figure 1: Illustration of the impact of spherical particle on the water phase.

As seen from Fig. 1 the particle deforms the interface and forms a funnel shape oil filament behind it. After some times this filament of oil funnel pinches off and ultimately oil droplets are formed and released from the funnel and continues to rise to the oil phase. These oil droplets rise very slowly. These phenomena are also illustrated in Fig. 2. In this case, the particle is entering the fluid with a velocity U_b and draws out a funnel shaped air behind it[2]. It can be seen from the illustration that the narrowest part of the funnel is closest to the particle.

This phenomenon has been identified as a buckling instability due to the fluid elasticity[3]. The elasticity at the interface might indicate that there is a viscoelastic stretching of the lower fluid. This implies that the oscillations of the particle at the interface should not be surprising. This was observed in our experiments where the particle initially stopped as it crosses the interface, bounces ups and downs one or more times before it sinks down to the lower fluid.

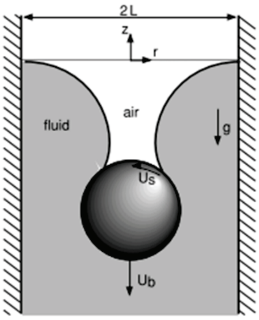

Figure 2: Deformation of the interface when a sphere sinks through a fluid. Adapted from Podgorski and Belmote[2]

EXPERIMENTAL

Experimental setup

Figure 3 shows a schematic representation of the setup. The experimental fluids used are mineral oil and water or by water based polymer solutions. The system can be divided in three regions. In the region 1 mineral oil, Bayol 35 with density of 0.7922 g/l and 1.030 cP, was used as the upper fluid. In region two water or by water based polymer solutions was used as lower fluid. The polymer solution is Poly Anionic Cellulose (PAC) dissolved in water. Between those two regions is established an interface where the instability occurs. The oil layer is open to the atmosphere. For a quantitative exploration of the phenomena, the fluids were placed in a graduated cylinder. 800 mL was filled in with water and the rest 200 mL with oil. The experiments were performed at room temperature of 20°C. The particle was held immersed in the oil phase using a spoon and released gently in the upper fluid to avoid initial velocity. It then starts to sink in the upper fluid first and then crosses the interface by deforming it. Furthermore, the particle pulls the interface down as the instability develops.

The experiments have been performed

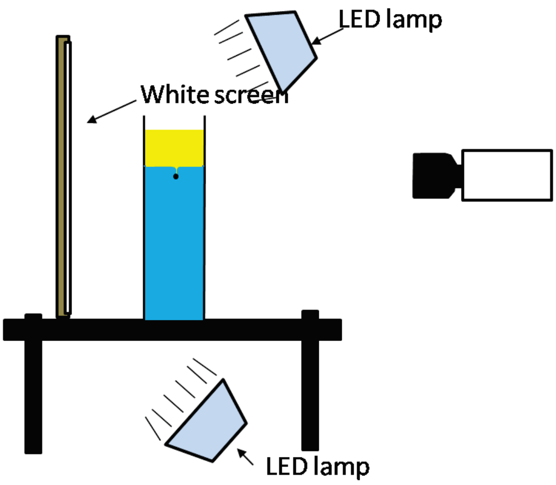

Figure 3: Experimental setup.

with different a variety of spheres having different densities and diameters[4]. But only 3 mm glass bead particle is presented in this paper, as seen in Fig. 4 since similar behavior was obtained during observations of other types.

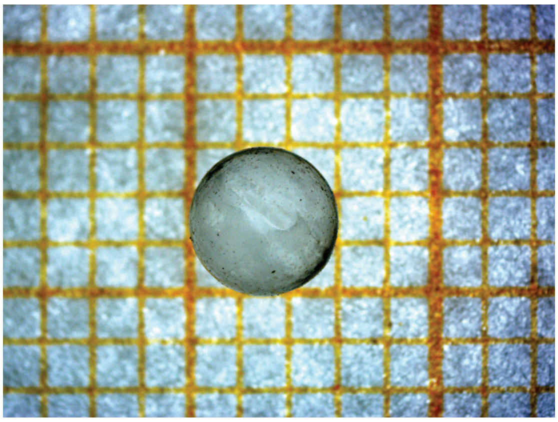

Figure 4: 3mm glass bead particle used in the experiment. The density of the particle is 2.594 g/ml[4].

Johnsen[4] conducted tests with other particles ranging from 200μm to 15 mm regarding sphericity, hollowness. These were done to avoid buoyancy effects as well as surface roughness that could lead to frictional effects.

Visualization was obtained using a low cost camera (Samsung EK-GC 100, 768 x 512 pixels 120fps in slow motion video mode) and LED lamps. This is a simple and inexpensive system that probably can substitute expensive equipment to achieve high accuracy as compared with high cost and complex system.

Particle Shadow Velocimetry (PSV) is introduced in this paper to be an alternative to Particle Image Velocimetry (PIV). The LED lamps are directed toward a white surface and shine towards the camera. This systems allows low power illumination sources such as LEDs which are inexpensive and produces no glare effects nor reflections from surfaces. In addition this method provides good contrast images of the particle.

Fluid rheology

The lower fluid used is water and Poly Anionic Cellulose (PAC) dissolved in water. 4 and 8 g/L of PAC were mixed for a day and then allowed to set for a day before use. The rheological characterization of the polymeric solutions was done using an Anton Paar MCR-302 for shear rates ranging from 1 to 1020 s^{-1}. Cone plate geometry CP50-1 was used for performing the experiments at 20^{o}C. The measurements were repeated several times to get rid of experimental uncertainty. The viscosity as a function of shear rate is graphed in Fig. 5 for these two solutions. It can be seen from this figure that the polymer solutions are shear thinning.

For each solution, the focus was on the fluid dynamics around the particles, as mentioned earlier.

Image analysis

The PIV technique for studying and measuring the flow around the particle has been covered elsewhere[4]. It is described by Johnsen[4] and Rabenjafimanantsoa and Time[5] but we recall it here for brevity. The PIV system includes a Suwtech continuous wave (CW) diode laser giving a beam with 532nm wavelength. The beam

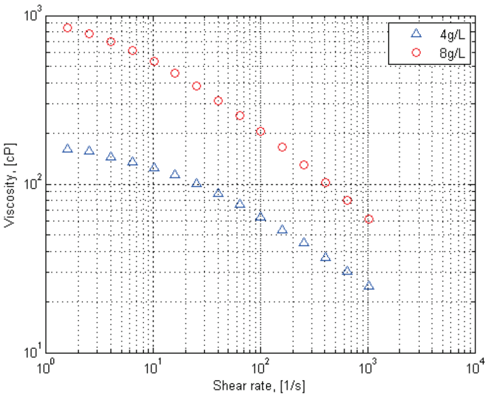

Figure 5: Loglog plot of viscosity versus shear rate at 20^{o}C of the 4g/L and 8g/L concentrations of PAC dissolved in water.

is collimated into a 1mm thick and 5cm wide, nearly parallel "light sheet", using two cylinder lenses. The beam energy is adjustable up to 200mW using a Photop LDC-2500S power supply. A high speed camera (MiniVis e2, 512x512 pixels, 2500 fps) was computer controlled using the software program MotionBlitz from Mikrotron, to record series of pictures. In addition and most employed in this study, light emitting diodes (LEDs) were set up to direct towards a white surface behind the cylindrical graduated column. This was done to avoid glare effects or reflections from the glass surfaces.

EXPERIMENTAL RESULTS

In these experiments the wake of a single particle falling through the oil phase and crossing the interface of the polymeric fluid is of interest. Similarly to Johnsen[4] and Akers and Belmonte[6], in pure water only, a sphere forms a cavity as it enters the fluid. It entrains some air and continues to sink. Similar observations have been seen for rising bubbles[5]. As the bubble crosses the interface it entrains the aqueous phase into the oil phase. This entrainment occurs in the form of a film around the bubble which broke up and fall down to the oil water interface.

The sequence of events during the release of the glass bead particle through the interface and impact on the water-based polymeric fluid is summarized in Fig. 6. The particle is held initially at the top and

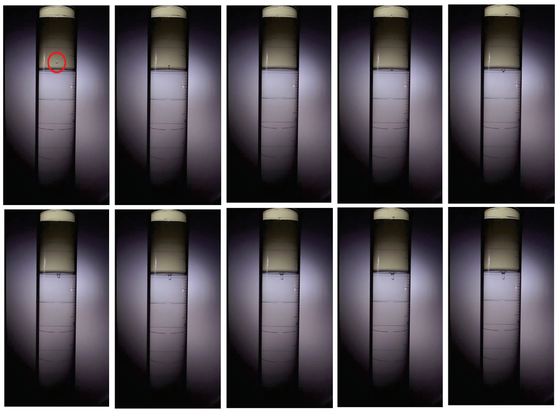

Figure 6: Sequential images of the crossing of the 3 mm glass particle (encircled) dropped from the top of the oil phase into the polymer phase. The time between images is 8.3 ms

released into the oil phase. It then slows down as it crosses the interface.

A close up view of the last sequence of images in Fig. 6 is shown in Fig. 7.

Figure 7: Close up view of the 3 mm glass particle showing the cavitation after crossing the oil phase into the polymer phase.

As seen in Fig. 8 the time evolution of the particle position just before and after its impact at the interface is presented. The height represents the particle position

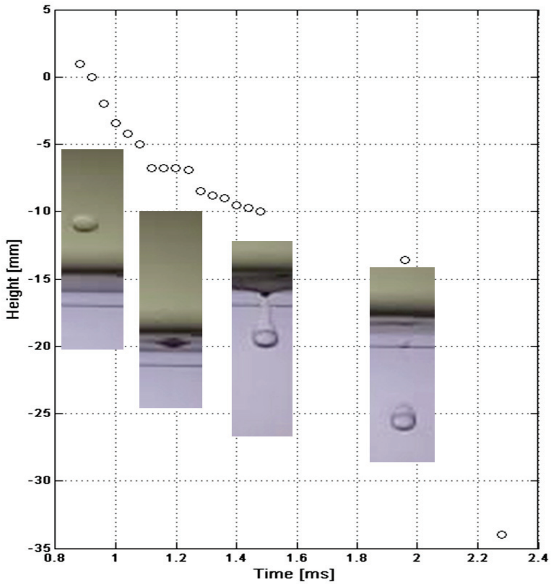

Figure 8: Particle dynamics before and after crossing the interface.

as a function of time. The particle initially enters into the oil from t = 0.88ms and slows down at the interface. Between t = 1.12 and 1.24ms the particle is almost stopped at the interface. The particle bounces upwards one or more times at the interface on top of the PAC fluid before it sinks down into the aqueous phase. It is nearly stopped probably due to the fluid elasticity. The cavity is formed by the particle as soon as it enters the aqueous phase. This is referred to as a result of the buckling instability[2]. As the particle continues sinking it drags down oil from the upper layer. At t = 1.28ms the filament has grown to be approximately 1cm long. It takes the shape of a funnel where the narrowest part is attached to the interface. The funnel is axisymmetric as seen in Fig. 8 at t ≈ 1.4ms. The evidence of this observation could be related to the elasticity of the fluids. However, this observation is in contrast with Akers and Belmonte[6] where they experiment the narrowest part of the funnel to be somewhere above the sphere. Figure 9 gives evidence of the funnel shaped filament showing the narrowest part attached to the interface between oil and PAC. As seen in Fig. 8 at t ≈ 1.4ms relatively large amount of oil cavity is entrained behind the falling particle. Beyond t = 1.48ms oil drops that were attached to the filament rise upwards through the PAC fluid. The particle with a cavity of oil attached to it continues to sink in a rectilinear manner.

Figure 9: High speed image of the funnel shaped filament attached to the particle. Oil drops are shown (encircled). The image frequency is 1500 Hz.

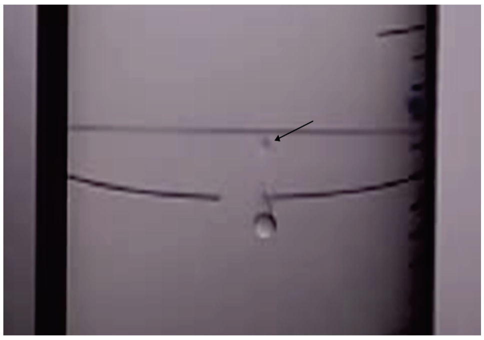

Figure 10: Example of oil drop (shown by the arrow) released from the cavity at 9.16ms.

As seen in Fig. 10 at t = 9.16ms an example of oil drop is released from the cavity. The high speed image in Fig. 9 clearly demonstrates both the interface deformation and the oil drops (encircled) raising back to the oil phase. Although the dynamics of this oil drop rising back to the oil layer was not yet a direct focus on this study but our observation reveals that they are spherical in shape as they rise through the PAC fluid.

In addition, Grumstrup *et al.*[7] reported the existence of ripples of air cavity entrained by solid object in liquid. Similar situation was not observed in this study but their origin could be attributed to the surface tension and needs further investigation. At t = 1.48ms (height = -10 mm) rupture occurs.

CONCLUSIONS

Experimental studies of the passage of particles and spheres in two immiscible fluids are presented in this paper. 4 and 8/L of PAC dissolved in water have been used for demonstrating the effect of non-Newtonian fluid. The 3mm glass particle sinks through the oil phase and drags a thin funnel-shaped filament along it through the aqueous phase. At a later stage the filament breaks down and an oil cavity is attached to the particle

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