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Deformation of an oil droplet on a solid substrate in simple shear flow

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ABSTRACT

Displacement of immiscible fluids is important in sub-surface processes such as enhanced oil recovery, oil sand processing and detergency. In this study, simulation of an oil droplet deformation on a solid substrate in simple shear flow has been carried out using computational fluid dynamics tool (Fluent 6.3) and the shape of the oil droplet is compared with that of the experimental observation. The dynamic behavior of a two-dimensional oil droplet subject to shear flow in a closed channel is considered under the condition of negligible inertial and gravitational forces. The volume of fluid method is used in Fluent to determine the dynamics of free surface of the oil droplet during the fluid flow. The oil droplet deformation increases with the increase in capillary number, Reynolds number and size of the oil droplet. The deformation of an oil droplet attached to channel surface in simple shear flow is studied experimentally in laminar flow through visual observation using microscope (Ziess, SV11 APO) with high speed camera (PCO). Aniline and isoquinoline was used to form oil droplet and distilled water was used as shearing fluid. The deformation of aniline and isoquinoline droplets was recorded using a high speed camera connected to a PC. The recorded image was replayed and the deformation of aniline and isoquinoline droplets was analyzed using Axio Vision software and compared with the results obtained from CFD simulation. The deformation of different sizes of aniline and isoquinoline droplets at different flow rates of shearing fluid and with time are well predicted by the CFD simulation.

1. Introduction

The phenomena of deformation and displacement of immiscible fluids on solid substrate take place in removal of oil droplets from the narrow passage of a porous rock structure in enhanced oil recovery. The ease of oil droplet deformation and displacement determines the efficiency of enhanced oil recovery or the transport of non-aqueous phase liquids through the rock structure via water or surfactant flooding. Apart from enhanced oil recovery, liquid droplets adhering to, moving along, or dislodging from solid surfaces are encountered in several natural and engineering settings and under a wide range of physical conditions such as detergency and cell detachment in human body. The fundamentals of oil droplet deformation and detachment are studied during last decade but most of the studies are restricted to theoretical model development. The experimental work with respect to visual observation of oil droplet deformation and displacement is scanty in openly available literature.

Dussan (1987) theoretically analyzed the phenomenon of a droplet dislodging from a solid surface in the presence of motion of surrounding fluid. Dussan (1987) developed yield criteria for the critical capillary number, *Ca*, as a function of the advancing and receding contact angles, θ_a and θ_r, for an oil droplet sliding on a plane. The capillary number, *Ca* $(=\mu_1 U/\gamma)$ is a ratio of viscous to surface tension forces, where γ is the oil–water interfacial tension, μ_1 is the viscosity of shearing fluid and U is the free stream velocity of shearing fluid. The analysis was based on asymptotic theory valid for small contact angle hysteresis $(\theta_a - \theta_r)$. Here, θ_a is the advancing contact angle and θ_r is the receding contact angle of oil the droplet. Mahe et al. (1988) studied experimentally the attachment and detachment processes of different alkane droplets having different contact angles on glass surface in simple shear flow. They mainly focused on visual observation of detachment of an inverted oil droplet from a solid substrate by viewing the contact area through a microscope. They observed that the oil droplet adhered to the solid substrate having equilibrium contact angle close to 180° deforms and leans in the direction of shear. The contact angle of the advancing edge (θ_a) increases, whereas that for the receding edge (θ_r) decreases. And finally the droplet detaches when the receding edge slides and meets the advancing edge at the downstream side of the droplet.

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Mahe et al. (1988) presented the data in terms of shear rates required for the detachment of different sizes of oil droplets. Feng and Basaran (1994) theoretically modeled translationally symmetric cylindrical bubble protruding from a slot in a solid wall into liquid undergoing simple shear flow. They solved two-dimensional Navier–Stokes equations by the Galerkin finite element method. The plot of bubble deformation versus Reynolds number (*Re*) is found to exhibit turning points, where *Re* reaches critical value. Li and Pozrikidis (1996) studied the three-dimensional analogue of the problem of Feng and Basaran (1994) in the limit of low *Re* using boundary integral method. They computed the shapes of droplets as a function of *Ca* for different geometries of the contact line. It is concluded that the droplet with elliptical contact line is likely to dislodge or breakup before the droplet with circular contact line. Basu et al. (1997) proposed a mathematical model for the detachment of non-wetting droplet ($\theta_e \sim 180^\circ$) and partially wetting droplet ($\theta_e \sim 120^\circ$) based on visual observation described by Mahe et al. (1988). According to Basu et al. (1997), a droplet detaches from solid substrate when the drag on the droplet due to motion of shearing fluid overcomes the retentive force due to the contact angle hysteresis and interfacial tension. However, a droplet having an equilibrium contact angle, θ_e, approaching 120° slides on the solid surface and does not detach. With further increase in the shear rate, the sliding droplet detaches from the solid surface when the lift force equals the adhesive, gravitational and buoyancy force of the droplet. The critical shear for the detachment of a pristine droplet, having θ_e of 175°, is reasonably predicted by the model where sliding as the mode of detachment is assumed, whereas the experimental data for squalane droplet, having θ_e of 126°, is reasonably predicted by the model where lift is considered as the mode of detachment. However, mathematical model developed by Basu et al. (1997) involves assumptions and hence it suffers from accuracy of prediction of oil droplet detachment in shear flow. Dimitrakopoulos and Higdon (1997) studied theoretically two dimensional droplet dislodging from a solid surface in shear field taking into account the gravity. They found critical shear rate of detachment as a function of viscosity ratio of droplet and shear fluids, Bond number ($=(\rho_2 - \rho_1)gR^2/\gamma$) and contact angle hysteresis. Schleizer and Bonnecaze (1999) used boundary integral method to determine droplet deformation on a solid surface in a shear field with fixed and mobile contact line for negligible gravity and inertia. The deformation of the droplet increases with the increase in capillary number, viscosity ratio and size of the droplet. They studied the effect of surfactant concentration on deformation of the oil droplet. The dynamics of partial detachment of oil droplet from solid surface is simulated by Jones et al. (1999) using dissipation particle dynamics approach. According to them, at a shear rate exceeding critical value, the oil droplet acquires tendency to lift off the surface leading to its removal.

Most of the studies mentioned above are mathematical models except for the work of Mahe et al. (1988), who observed the detachment process by viewing the contact area through a microscope. The droplet deformation is not visually observed from the side of the droplet. It is noted that contact angle hysteresis plays an important role and droplet tends to slide in the intermediate range of equilibrium contact angle of the oil droplet. Thus it is important to observe the deformation and detachment from the side of the droplet. Further, in most of the mathematical modeling work, experimental verification of the droplet deformation is not carried out. In the present study, the deformation and detachment of two different oil droplets, namely aniline and isoquinoline attached to a solid substrate in simple shear field were visually observed and droplet deformation were quantified. Finally, the droplet deformation in shear field was analyzed using computational fluid mechanics software (Fluent 6.3) and compared with the droplet deformation observed in the experiment.

2. Experimental

2.1. Material

Oil droplets used in the experiment were analytical grade aniline (E Merck) and isoquinoline (Spectochem). RO water of conductivity 15–30 μmho/cm obtained from Sartorius de-ionized water purification system (Sartorius, Arium 61315) was used as shearing fluid. The physical properties of the test fluids are given in Table 1.

2.2. Setup

Fig. 1 shows the schematic of the experimental setup used in visualization of droplet deformation and detachment in shear field. An overhead tank (a), with an arrangement to keep the water level at a constant height, was connected to a channel (d) of rectangular cross section through a rotameter (c). The dimensions of the channel are 1.4 m long and 35 × 56 mm^2 cross-sectional area. The channel dimension was such in comparison to size of the oil droplet (10–100 μL) that the effect of side walls, entry and exit length may be neglected. The range of flow rate used and dimension of the channel resulted in

Table 1
Physical properties of the test fluids (30 °C)

Test fluids	Density, ρ (kg/m^3)	Viscosity, μ (Pa s)	Oil–water interfacial tension, γ (mN/m)
Water	988.0	0.001	–
Aniline	1023.5	0.0034	5.27
Isoquinoline	1099.0	0.0029	0.6

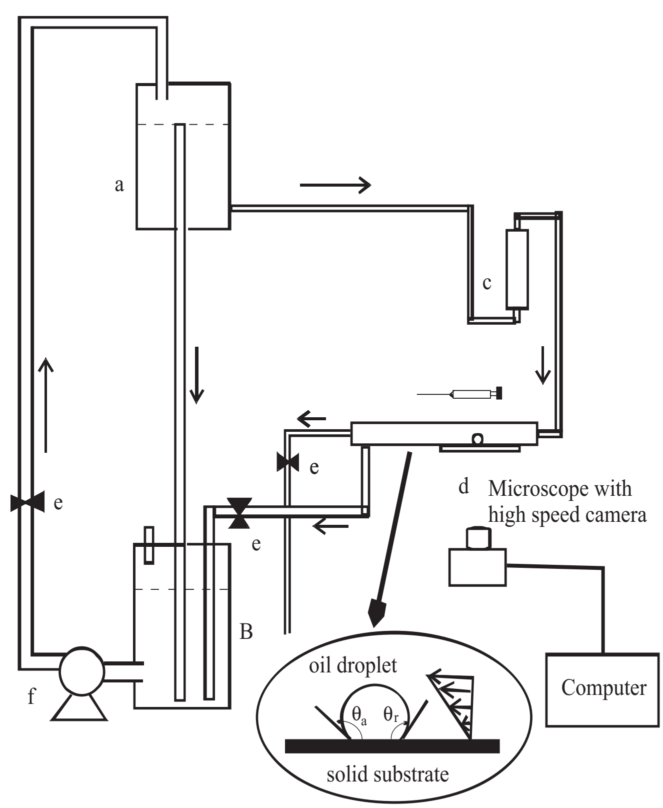

Fig. 1. Schematic diagram of the fluid flow loop for oil droplet deformation and detachment experiment. a: upper tank, b: bottom tank, c: flow meter, d: test section, e: valve, f: pump. θ_a = advancing dynamic contact angle, θ_r = receding dynamic contact angle.