Breakup of high solid volume fraction oil–particle cluster in simple shear flow

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HIGHLIGHTS

- Breakup of clusters with high volume fractions can be characterized as droplet breakup.
- A critical capillary number was obtained for oil–particle clusters to breakup.
- Systems with high viscosity ratios require longer shearing time for breakup.
- The liberated oil may coalesce with secondary clusters at low interfacial tensions.

GRAPHICAL ABSTRACT
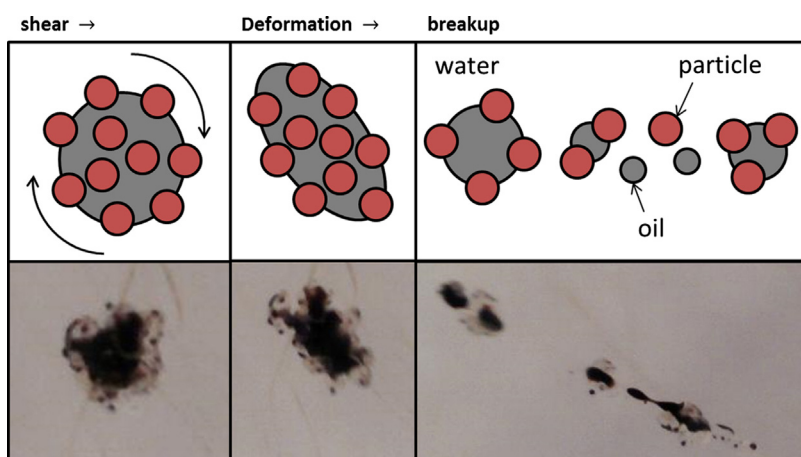
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ABSTRACT

Experiments were conducted of the low-Reynolds number breakup and separation of oil–particle clusters characterized by a high volume fraction of relatively large solid particles, under simple shear in an aqueous solution. The breakup of such oil–particle clusters, and the separation of particles from the clusters, are evaluated as a function of viscosity ratio of the oil phase to the aqueous solution, interfacial tension, and shearing time. When the viscosity ratio is high, clusters are more difficult to breakup, a longer shear time is needed, and few particles detach. At low viscosity ratios, clusters are easily deformed and break up into smaller clusters, and more clean particles detach. Lowering the interfacial tension also facilitates the liberation of oil droplets from particles.

The results show that the breakup of oil–particle clusters with a high volume fraction of large particles can be characterized as simple droplet breakup, meaning that the viscosity of the oil governs the dynamics of the cluster, rather than an effective viscosity that is a function of the solid volume fraction. The degree of cluster breakup and the separation of particles from the primary cluster is related to a cluster-based capillary number and the viscosity ratio. There is a critical capillary number required to obtain clean particles.

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Nomenclature

Ca	capillary number
Ca_{crit}	critical capillary number
h	gap between the plates (m)
i	number of secondary clusters
K	power law constant (Pa s^n)
n	power law index
p	viscosity ratio
r	distance of the cluster from the center of the plates (m)
R	radius of the projected area of the cluster (m)
V_o	oil volume within the cluster (m^3)
V_s	solid particle volume within the cluster (m^3)
$\dot{\gamma}$	shear rate (1/s)
μ_1	aqueous solution viscosity ratio (Pa s)
μ_2	oil viscosity (Pa s)
σ	interfacial tension (N/m)
ϕ	volume fraction
ω	angular velocity (rpm)

1. Introduction

Oil–particle clusters are encountered in many industrial processes including the treatment of mineral slurries, the remediation of oil-based drill cuttings, and the processing of oil sands. In oil sands extraction [1,2], for example, the objective is to separate bitumen (the oil phase) from solid particles by mechanical means such as mixing and flotation in an aqueous environment. Bitumen extraction from oil sands is often aided by high temperatures and the addition of solvents to reduce the viscosity of bitumen, and the addition of surfactants to reduce the interfacial tension of bitumen, to facilitate oil–particle separation.

The oil phase between solid particles in oil–particle mixtures forms liquid bridges that exert capillary forces binding the particles. The thermodynamic stability of such clusters of solid particles bound by a dispersed fluid has been previously studied [3–7]. The effects of interfacial tension, particle size, temperature, pH, solvent dilution and particle wettability on oil–particle interaction in batch conditions have also been studied extensively from chemical and thermodynamic points of view [8–16]. Bitumen recovery improves dramatically with increasing temperature because bitumen viscosity decreases sharply [11,12]. Increasing pH facilitates the separation of bitumen from solid particles [8,11]. The addition of solvent improves the separation because it reduces the viscosity of the oil and increases the volume of the oil, which increases the area upon which external shear forces can act [11]. Finally, the addition of surfactant decreases the interfacial tension, which is the cohesive force holding clusters together, and aids recovery [13–15].

This study focuses on the separation process at the scale of single oil–particle clusters, from a hydrodynamic standpoint, an aspect not considered by the studies mentioned earlier. We examine the low Reynolds number breakup of oil–particle clusters at very high solid volume fraction, with relatively large particles, under shear in an aqueous solution. The oil–particle clusters consist of bitumen mixed with beach sand particles. The solid volume fraction is close to that of Alberta oil sands ($\approx$72%), and greater than any previous study on oil–particle clusters [17–22].

The particle size relative to the cluster size, and the solid volume fraction ϕ are two important parameters that determine the fate of clusters. When the particle size relative to the cluster size is small, so that the cluster can be considered as a continuum then clusters undergoing shear behave like a liquid drop with a viscosity governed by ϕ [18–20]. Bonnoit et al. [20] investigated the

effect of both these parameters when they studied the detachment of drops from dense granular suspensions (clusters). Their results showed that the initial deformation of the cluster highly depends on ϕ, i.e. higher ϕ leads to a more viscous cluster, and hence slower deformation. Whereas, at later times, close to the breakup time, the deformation is independent of ϕ and only depends on the viscosity of the oil phase. Also, clusters breakup significantly faster than pure oils matching the same viscosity, because the presence of the particles within the cluster prevents the formation of a long, stable filament. Their results also showed that larger particles lead to faster breakup.

Smith and Van de Ven [18] and Powell and Mason [19] studied the behavior of clusters in simple shear flow and elongational flow, respectively. The shear flow fields in [18] and [19] are more relevant to the shear flow studied in this paper. At low ϕ, the particles within the cluster rearrange themselves due to the internal circulation. These particles tend to accumulate at the tips of the cluster and are ejected if the shear stresses are strong enough [18]. As ϕ increases, the movement of particles within the cluster decreases due to the particle–particle interaction. For simple shear flow, if the shear stresses are strong enough the cluster breaks up into two equally sized clusters [18], and for elongational flow, the cluster deforms into a long cylindrical shape which pinches at regular intervals along its length [19]. No cluster rupture is seen when $\phi > 0.5$, and only some particles on the outside of the cluster are pulled from the surface, because they are partially coated [18].

Various equations have been proposed to represent the viscosity of solid–liquid suspensions (or clusters) [23–29]; however, these equations are only valid when the ratio of the particle size to the cluster is small, so that the cluster can then be considered as a continuum. This study, on the other hand, focuses on clusters where the particle size relative to the cluster size is large $O(0.1)$, so that the cluster cannot be considered as a continuum. We will show that for systems with high ϕ and relatively large particles, the viscosity of the oil alone governs the dynamics of the deformation and the breakup of the cluster.

The addition of surfactants is commonly used to enhance the separation of oil–particle–water systems. Surfactants absorb at oil–water interfaces and not only change the interfacial properties of the two liquid phases, but can also modify the wettability of solid particles. Surfactants can aid the separation of oil from solid particles via three different mechanisms: roll-up, snap-off, and solubilization [30–33]. In the roll-up mechanism, shown in Fig. 1a, the solid particle is preferentially water-wetting (contact angle greater than 90), meaning that the oil does not wet the solid, and so when a three phase contact line forms, the oil recedes until it detaches from the surface. Snap-off, shown in Fig. 1b, occurs when the oil partially or completely wets the surface (oil-wetting) and the hydrodynamic forces are strong enough to remove a portion of the oil from the
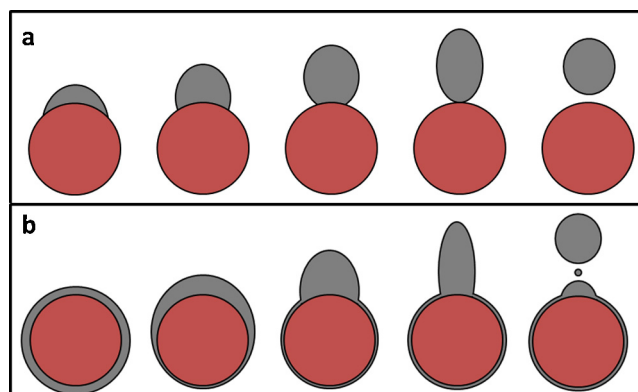

Fig. 1. Illustration of the (a) roll-up and (b) snap-off mechanisms.