



# Oil-particle separation in a falling sphere configuration: Effect of viscosity ratio & interfacial tension



Sasan Mehrabian<sup>a</sup>, Edgar Acosta<sup>b</sup>, Markus Bussmann<sup>a,\*</sup>

<sup>a</sup> Department of Mechanical and Industrial Engineering, University of Toronto, Toronto, Ontario M5S 3G8, Canada

<sup>b</sup> Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Ontario M5S 3E5, Canada

## ARTICLE INFO

### Article history:

Received 12 April 2017

Revised 9 September 2017

Accepted 11 September 2017

Available online 15 September 2017

### Keywords:

Bitumen

Oil sands

Capillary

Oil-coated particle

Separation

## ABSTRACT

The separation of oil from a single oil-coated spherical particle falling through an aqueous solution is evaluated as a function of viscosity ratio and interfacial tension. A solvent was used to modify the viscosity of the oil and a surfactant was used to modify the interfacial tension. The separation process is characterized with respect to a capillary number (ratio of viscous shear stress to interfacial tension) and the viscosity ratio (between the oil phase and the aqueous solution). The separation of oil from the falling sphere can be described as a two-stage process. The first stage is the deformation of the oil film coating the sphere, leading to the formation of a thread or “tail” downstream of the particle. The second stage involves the breakup of that tail as the sphere falls. The initial film deformation and tail formation is best described by a capillary number based on the shear rate at the oil-water interface; and the tail breakup by the rate of elongation experienced by the tail. More oil is removed when thicker tails are formed, which are obtained at high viscosity ratios. However, high viscosity ratios require longer shearing time for the tail to form. Our results indicate that maximum separation takes place when the viscosity ratio is between 0.1 and 1, with capillary numbers close to 1.

© 2017 Elsevier Ltd. All rights reserved.

## 1. Introduction

The separation of oil from particles is encountered in many industrial processes including the treatment of oil sands (Dai and Chung, 1995; Masliyah et al., 2010) and the remediation of oil spills (Fingas, 2012; Quraishi et al., 2015). The main objective of these processes is to separate the oil and particles via mechanical means such as mixing in an aqueous solution, plus the addition of heat and chemicals. The efficiency of separation not only depends on the processing method, but also on the thermo-physical properties of the system, such as the viscosities and interfacial tension of the two fluids, and the wettability of the solids. The separation of oil from sand particles has been well studied from thermodynamic and chemical standpoints. For example, the effect of temperature, solvents, and surfactants are well understood (Dai and Chung, 1995; Long et al., 2007; Niven et al., 2000a; 2000b; Quraishi et al., 2015; Schramm and Kwak, 1988; Schramm et al., 2003a; 2003b; Stasiuk and Schramm, 2001). These studies help to identify the important mechanisms that lead to separation. However, there are only a few publications in the literature that con-

sider the separation process from a hydrodynamic point of view (Bertrand et al., 2012; Bonnoit et al., 2012; Fan et al., 2010; Mehrabian et al., 2015; Powell and Mason, 1982; Smith and Van de Ven, 1985a; 1985b; 1985c; Thareja and Velankar, 2008), and perhaps a more efficient separation would be achieved if the effects of hydrodynamics were also taken into consideration during the design of separation processes. The objective of this work is to study the separation process in a well-defined flow field, from a hydrodynamic standpoint.

Little research has been conducted on oil-particle-water systems at small scales to understand the separation process fundamentally. To the best of our knowledge the work of Fan et al. (2010) and Smith and Van de Ven (1985b) are the only studies that examine the deformation and separation of an oil layer coating a spherical particle in well-defined flow fields. Considerable research, however, has been done on the breakup of a solid/liquid cluster and separation of oil from a cluster in well-defined flow fields (Mehrabian et al., 2015; Powell and Mason, 1982; Smith and Van de Ven, 1985a; 1985c; Thareja and Velankar, 2008).

In a previous paper to this one (Mehrabian et al., 2016), separation was examined as a function of the initial thickness of the oil coating the sphere, at low Reynolds numbers ( $Re = 2\rho_1 U_\infty R_0 / \mu_1 <$

\* Corresponding author.

E-mail address: [bussmann@mie.utoronto.ca](mailto:bussmann@mie.utoronto.ca) (M. Bussmann).

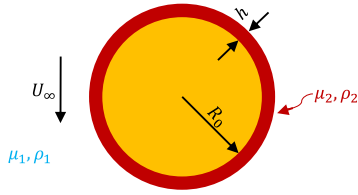


Fig. 1. Oil-coated solid sphere falling through an aqueous solution.

1), and it was shown that the fraction of separated oil increases with increasing initial oil thickness. In this work we examine separation as a function of viscosity ratio and interfacial tension. A schematic of the problem is shown in Fig. 1.

Similar to the deformation and breakup of isolated droplets, the separation of oil from solid particles in well-defined flow fields (e.g. Couette flow) depends on a capillary number, that expresses the ratio between the viscous shear stress and the interfacial tension, and the viscosity ratio  $p = \mu_2/\mu_1$ . The viscous shear stress  $O(\mu_1 \dot{\gamma})$  works to shear and deform the oil, while the capillary pressure  $O(\sigma/R_0)$  opposes the deformation of the oil film. When a solid phase is added to a liquid droplet, deformation becomes more complex and will also depend on the thickness  $h$  and the viscosity of the oil  $\mu_2$ . An explicit relation for a particle-based capillary number  $Ca_p$ , based on the velocity of the oil-water (O/W) interface, is presented by Mehrabian et al. (2016), and is a function of the dimensionless film thickness  $\varepsilon = h/R_0$  and viscosity ratio  $p = \mu_2/\mu_1$ :

$$Ca_p = \frac{\mu_1 \mathbf{U}_{O/W}}{\sigma} = g(\varepsilon, p) \frac{\mu_1 U_\infty}{\sigma} \quad (1)$$

where

$$g(\varepsilon, p) = \frac{15\varepsilon + 15\varepsilon^2 + 4\varepsilon^3}{2[15\varepsilon + 15\varepsilon^2 + 4\varepsilon^3 + p(20 + 30\varepsilon + 18\varepsilon^2 + 4\varepsilon^3)]}$$

$\mu_1$  and  $\mu_2$  are the viscosities of the aqueous solution and dispersed phase (oil drop), respectively,  $\mathbf{U}_{O/W}$  is the interfacial velocity,  $U_\infty$  is the terminal velocity,  $\sigma$  is the interfacial tension between the oil phase and aqueous solution, and  $g(\varepsilon, p)$  is a function that depends on  $\varepsilon$  and  $p$ .

The system under investigation here can be understood by the considerable literature on the deformation and breakup of isolated droplets in well-defined flow fields. Many aspects of the deformation and breakup of isolated droplets have been extensively studied, including: the critical conditions for droplet breakup (Bentley and Leal, 1986a; 1986b; Grace, 1982; Hinze, 1955; Zhao, 2007), the effects of surfactants (Milliken et al., 1993; Stone and Leal, 1990b), and the breakup of liquid threads (Rumscheidt and Mason, 1962; Stone et al., 1986; Tomotika, 1935). Hadamard (1911) and Rybczynski (1911) obtained analytical expressions for the flow inside and outside a spherical droplet translating in a quiescent liquid. Acrivos and Lo (1978); Cox (1969); Rallison and Acrivos (1978); Taylor (1932, 1934) and Frankel and Acrivos (1970) all present analytical models of the steady drop shape at small deformation, and Stone and Leal (1990a) and Davis and Brenner (1981) studied the deformation of drops containing an internal phase. Many of these studies have been reviewed by Rallison (1984); Stone (1994), and Eggers and Villermaux (2008).

Of particular relevance to this study, the minimum shear required for droplet breakup takes place when  $0.1 < p < 1$  (Grace, 1982). In a simple shear flow, droplet breakup becomes impossible when  $p > 3$ , regardless of the magnitude of the shear; in an elongation flow, droplet breakup can take place at any  $p$  as long as  $Ca > Ca_{crit}$  (Grace, 1982). Recently (Zhao, 2007) reported different modes of drop breakup as a function of  $p$  and  $Ca$  for drops in a simple shear flow field. The highlight of this paper is that for

$Ca > 2Ca_{crit}$  and  $p < 0.1$  droplet breakup results in re-breaking and collision of the droplets, and as  $p$  decreases, more re-breaking and collision occurs.

When surfactants are introduced, they absorb at interfaces and lower the O/W interfacial tension  $\sigma$ , which enhances droplet breakup. However, research has shown that the presence of surfactants changes other properties of the system and not just the interfacial tension (Milliken et al., 1993; Stone and Leal, 1990b), and that a similar degree of deformation should not be expected at the same capillary number achieved without the use of surfactants. Consequently, the presence of surfactants alters the oil droplet shape and different deformation/separation mechanisms can take place. Smith and Van de Ven (1985b) showed that in oil-particle-water systems, surfactants absorb both at the oil-water and the particle-water interfaces, which lowers the interfacial tension between the liquids and also affects the contact angle, that leads to greater deformation/separation. Tasoglu et al. (2008) studied the effect of soluble surfactant on the velocity of a buoyancy-driven bubble, and concluded that surfactants generally increase the drag force leading to a reduction in terminal velocity.

In our previous work (Mehrabian et al., 2016), we examined the separation of oil from a solid particle in a falling sphere configuration from a hydrodynamic standpoint, as a function of the oil film thickness  $\varepsilon = h/R_0$ . We extend the study to examine the effect of viscosity ratio  $p = \mu_2/\mu_1$  and interfacial tension  $\sigma$ . In what follows, we briefly describe the experimental setup and methodology, and then present our results.

## 2. Experimental methodology

The experimental apparatus is a  $10 \times 10 \times 42$  cm<sup>3</sup> acrylic tank that contains an aqueous solution (Fig. 2). An electromagnetic device sits at the top of the tank, to serve as the release mechanism for an oil-coated solid sphere. Each experiment began with a sphere at rest and completely immersed in the aqueous solution. Steel spheres were used, with an average diameter of 4.26 mm (standard deviation of 0.0238 mm), and a density of 8302.7 kg/m<sup>3</sup> (standard deviation of 123 kg/m<sup>3</sup>).

Coker feed bitumen was used as the oil phase. Details on the composition of bitumen are presented elsewhere (Akbarzadeh et al., 2005; Kiran et al., 2011). The bitumen was diluted with toluene at different concentrations to study a wide range of viscosity ratios. The aqueous solution contained 2.5 wt% of the water-soluble polymer Carboxymethyl Cellulose (CMC) with different concentrations of Sodium Chloride (NaCl) and Sodium Dihexyl Sulfosuccinate (SDHS). The density of the CMC solution is 1000 kg/m<sup>3</sup>, and did not change significantly by varying the concentration of NaCl or SDHS. The densities of the oil phases used are reported in Table 1. A Carri-Med Rheometer (4 cm cone and plate geometry, with a cone angle of 2°) was used to measure the viscosity of both the oil phase and the CMC solution. The oil phase (bitumen + toluene) is a Newtonian fluid; the CMC solutions are non-Newtonian and follow the power law equation  $\tau = K\dot{\gamma}^n$ , where  $K$  is the consistency index,  $n$  is the power law index, and  $\dot{\gamma}$  is the average shear rate for a falling sphere. A full investigation of the rheology of the CMC solution is presented in Mehrabian et al. (2016). For a sphere of radius  $R_0$  falling at a terminal velocity  $U_\infty$ , the equivalent viscosity of a non-Newtonian fluid is (Chhabra, 1993; Chhabra and Richardson, 1999; Lali et al., 1989):

$$\mu_1 = K \left( \frac{U_\infty}{2R_0} \right)^{n-1} \quad (2)$$

To study the effect of interfacial tension, 3 wt% Sodium Chloride (NaCl) and different concentrations of Sodium Dihexyl Sulfosuccinate (SDHS) were added to the aqueous solution. NaCl was added to optimize the performance of the surfactant (Kiran et al., 2011).

Download English Version:

<https://daneshyari.com/en/article/4994854>

Download Persian Version:

<https://daneshyari.com/article/4994854>

[Daneshyari.com](https://daneshyari.com)