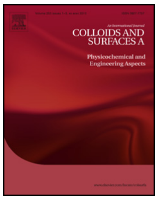
Colloids and Surfaces A: Physicochem. Eng. Aspects 497 (2016) 126–132

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa



Oil capture from a water surface by a falling sphere

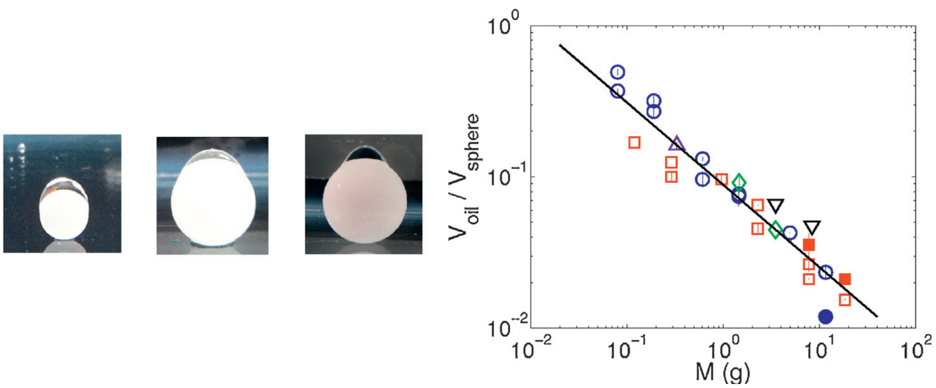
Linda B. Smolka[a],*, Clare K. McLaughlin[a], Thomas P. Witelski[b]

[a] Department of Mathematics, Bucknell University, Lewisburg, PA 17837, USA
[b] Department of Mathematics, Duke University, Box 90320, Durham, NC 27708, USA

HIGHLIGHTS

- The oil captured by a falling sphere that passes through an oil lens is measured.
- The volume of oil captured by the sphere increases with increasing sphere radius.
- The oil volume relative to the sphere volume decreases with increasing sphere mass.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 November 2015
Received in revised form 1 February 2016
Accepted 19 February 2016
Available online 23 February 2016

Keywords:
Oil capture
Pendant drop
Drop shape
Interface
Young–Laplace equation

ABSTRACT

Motivated by contaminant remediation, we study the volume of oil (oleic acid) removed from a liquid lens by a falling particle. When a spherical particle is dropped from a fixed height into an oil lens that floats on top of a water surface, a portion of the oil adheres to the sphere. Once the sphere comes to rest at the subsurface, the oil forms an equilibrium pendant drop that remains attached to the sphere. We find in experiments with spheres of different sizes and materials, that the pendant drop volume is an increasing function of sphere mass for each material and a decreasing function of sphere density. By contrast, the *normalized droplet volume* in all of our experiments scales with sphere mass following $V_{\text{oil}}/V_{\text{sphere}} \sim M^{-0.544}$. Thus, for a given size, lighter spheres capture more oil relative to their own volume than do heavier spheres and are more efficient at removing oil from a water surface in our experiments. Estimates for the upper bound of the normalized droplet volume, determined from the continuous family of solutions of the Young–Laplace equation, show the same qualitative dependence on the sphere mass.

1. Introduction

Contaminant remediation from an air-water interface is an active field of research whose interest was renewed after the 2010 Deepwater Horizon oil spill in the Gulf of Mexico. Studies have considered the role particles play in moving contaminant from the surface to the subsurface by suspended particulate material residing in the fluid column [1–3], by dropping sand onto an oil spill (the sand-sink method) [4], and by granular rafts of oil drops encapsulated by sand particles [5].

In this experimental study, we consider a simple model problem to the sand-sink method in which one spherical particle is dropped through an oil patch (or oil lens) that floats atop a water surface

---

* Corresponding author.
E-mail addresses: lsmolka@bucknell.edu (L.B. Smolka), witelski@math.duke.edu (T.P. Witelski).

http://dx.doi.org/10.1016/j.colsurfa.2016.02.026
0927-7757/

Fig. 1. Pendant drops of oleic acid are attached to the top of delrin spheres. The spheres, which sit at the bottom of a tank of water, have radii (left-to-right): R = 0.238 cm, 0.476 cm and 0.953 cm. The images are not at the same scale.

and address two fundamental questions: How effective is a single particle in removing oil from the water surface? Is there an optimal particle size that maximizes the capture of oil from the water surface? We examine particles of different sizes and materials in order to determine the key parameters that control oil entrainment by a sphere and to choose the particle size and material to optimize this. This model problem is analogous to sphere coating in which a sphere passes through an interface between two immiscible liquids of different viscosity [6].

Approaches for using sand to capture oil from a water surface are more complicated than by a single spherical particle as it involves the sedimentation of a dispersion of particles [7–9]. Numerous factors arise in sedimentation, including the dependence of the transport properties of a two-phase flow on the interactions between particles [10] and the dependence of the particle dynamics on the Reynolds number [11,12]. Particle interactions are even more complicated in the presence of oil due to the capillary forces exerted between particles [13–16]. Determining the volume of oil captured is further complicated by the fact that collisions between particles can effect the number and size distribution of droplets attached to the particles [17] and that the interstitial fluid joining spheres varies with sphere configuration, orientation, radii and contact angle at the three-phase contact line [13]. For the simplified problem of a single particle, these issues do not arise and we will focus on analysis of the pendant drop volume attached to the particle when it comes to rest at the subsurface.

We find oil adheres to the sphere after it passes through the oil lens forming a static pendant drop attached to the top of the sphere once the sphere comes to rest; examples are shown in Fig. 1. The shape of a pendant drop is governed by the Young–Laplace equation [18]. Solutions of the Young–Laplace equation compare well to experimental data for the quasi-static formation of drops and submerged bubbles on stationary planar, conical and spherical surfaces accurately predicting the profile and drop volume [19–25]. The Young–Laplace equation has been extensively used to determine the interfacial tension and contact angle formed at a three-phase contact line of axisymmetric pendant drops at gas–liquid and liquid–liquid interfaces [18,26–32]; methods include axisymmetric drop shape analysis [26,29,30] (ADSA) and a non-gradient based algorithm [31]. We examine the continuous family of solutions to the Young–Laplace equation to determine theoretical upper bounds for the pendant drop volume and to assess the efficiency of oil capture by different particles.

The paper is organized as follows. In Section 2 we describe the experimental setup and procedures. In Section 3 we present experimental data for the pendant drop volume. In Section 4 we estimate upper bounds for the pendant drop volume from solutions of the Young–Laplace equation. Conclusions are provided in Section 5.

2. Experimental setup and procedure

The experimental setup consists of an open top water tank, spheres and a hand-held digital camera. At the beginning of each experiment, the tank (l × w × d = 31 cm × 15.7 cm × 20.8 cm) is washed with an industrial cleaner, dried and then filled 13 cm deep with tap water. For the majority of the experiments an oil lens of 350 μl of oleic acid (90%-grade Sigma–Aldrich, density ρ_o = 0.876 g/cm^3, surface tension γ_o = 32.5 dynes/cm at 20 °C [33]) is placed on the water surface ($\rho_w = 1.0$ g/cm^3, $\gamma_w = 72.8$ dynes/cm at 20 °C [33]). To ensure a sufficient supply of oil, a 500 μl lens of oleic acid was also tested for the two largest spheres. Based on our experimental results (Section 3), we believe that the volume of the oil lens is sufficiently large so that it does not limit the volume of the pendant drop attached to the sphere. Oleic acid spreads on a water surface (with spreading coefficient $S_{o/w} = 24.6$ erg/cm^2 at 20 °C [34]) making it difficult to precisely control its size; in the experiments the lens radius ranged between 0.86 and 1.48 cm. The room and water temperatures ranged between 22.6–24.1 °C and 19.4–24.7 °C, respectively.

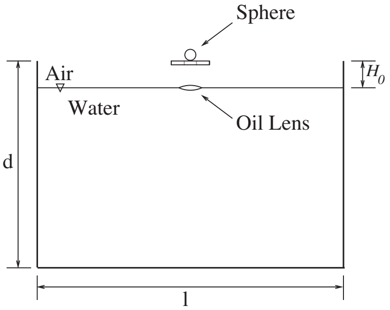


Fig. 2. Schematic of experimental setup with an open top water tank, sphere and oil lens. The sphere is dropped from rest through a 1.2 cm thick sleeve to ensure vertical entry.

Table 1
Spheres used in experiments: material, density and radii.

Material	ρ_s (g/cm^3)	R (cm)
Delrin	1.35	0.238, 0.318, 0.476, 0.635, 0.953, 1.27
Teflon	2.13	0.238, 0.318, 0.476, 0.635, 0.953, 1.27
Glass	2.41	0.318
Ceramic	3.25	0.476, 0.635
Steel	7.79	0.476, 0.635

A schematic of the experimental setup is shown in Fig. 2. In the experiments, the oil lens is centered below the sphere's release point and the sphere is released from rest a height H_0 = 5.9 cm above the water surface entering the water with impact velocity $U_0 \approx \sqrt{2gH_0} \approx 1$ m/s which is below terminal velocity in air. To ensure vertical entry, the sphere initially passes through a 1.2 cm thick sleeve. Each sphere is used only once.

Delrin, teflon, glass, ceramic and steel spheres (McMaster–Carr) ranging in radius from 0.238 to 1.27 cm are examined in our study. Table 1 lists the densities and radii of the 17 different types of spheres used. The specifications for these spheres does not provide information on their wetting properties, so we will estimate the degree of wettability via analysis of experimental profiles to obtain contact angles.

Digital images are recorded of the sphere at rest at the tank bottom as shown in Fig. 1. The interface between the water and the oil and sphere is located from these images using edge-detection software in ImageJ and MATLAB.

3. Experimental results

Once the sphere is at rest at the bottom of the tank the entrained oil forms a pendant drop. The pendant drop is attached to the top of the sphere since the density difference between water and oleic acid is positive, causing buoyancy to generate an upward force on