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Cleaning of viscous drops on a flat inclined surface using gravity-driven film flows

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ABSTRACT

We investigate the fluid mechanics of cleaning viscous drops attached to a flat inclined surface using thin gravity-driven film flows. We focus on the case where the drop cannot be detached either partially or completely from the surface by the mechanical forces exerted by the cleaning fluid on the drop surface. Instead a convective mass transfer establishes across the drop–film interface and the fluid in the drop dissolves into the cleaning film flow, which then transports it away. The characteristic time scale of dissolution is much longer than the advection time scale in the film flow. Thus, the shape and size of the drop can be considered as quasi-steady. To assess the impact of the shape and size of the drop on the velocity of the cleaning fluid, we have developed a novel experimental technique based on particle image velocimetry. We show the velocity distribution at the film surface in the situations both where the film is flowing over a smooth surface, and where it is perturbed by a solid obstacle representing a very viscous drop. We find that at intermediate Reynolds numbers the acceleration of the starting film is overestimated by a plane model using the lubrication approximation. In the perturbed case, the streamwise velocity is strongly affected by the presence of the obstacle. The upstream propagation of the disturbance is limited, but the disturbance extends downstream for distances larger than 10 obstacle diameters. Laterally, we observe small disturbances in both the streamwise and lateral velocities, owing to stationary capillary waves. The flow also exhibits a complex three-dimensional converging pattern immediately below the obstacle.

Keywords: Cleaning surfaces; Thin falling film; Flow over obstacle; Particle image velocimetry (PIV)

1. Introduction

Cleaning of fouling deposits using film flows is a common problem in many industrial processes, particularly in the food industry (see e.g. Wilson, 2005; Xin et al., 2002; Gillham et al., 2000). Fryer and Asteriadou (2009) explained that, in some cases, cleaning processes aim at overcoming cohesive forces within fouling deposits, as well as adhesive forces at the interface between a deposit and its substrate. Physical processes involve, for instance, fluid mechanical forces such as shear and pressure forces imposed at the deposit boundary by a liquid flow. Chemical processes can involve some material transport or diffusion and reactions. The shearing action of a film flow is often used to clean fouled surfaces in industrial processes (Yeckel and Middleman, 1987; Mickaily and Middleman, 1993). Dussan V. (1987) analysed the effect of a shearing immiscible fluid flowing over a drop. She derived theoretically the rate of strain beyond which the drop is swept away by the fluid.

However, we believe that in many cases the adhesive and cohesive forces maintaining a viscous droplet to be cleaned onto the substrate are stronger than the mechanical forces imposed by the cleaning film flow on the droplet. The pressure and shear forces exerted by the film flow at the interface with the drop cannot detach the droplet either partially or completely from the substrate. Therefore, the physics of the

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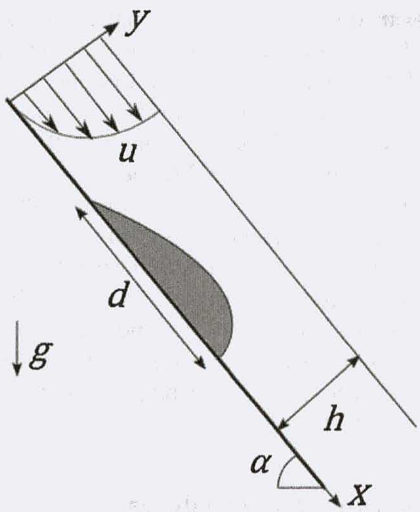

Fig. 1 – Schematic diagram of the cleaning problem. A liquid film flows over a viscous drop (shaded).

cleaning process, or removing of the droplet material by the film, is different and usually slower as it involves dissolution, diffusion and advection processes. A convective mass transfer from the droplet into the film occurs. The drop material slowly dissolves into the film and a diffusive boundary layer establishes above the interface separating the drop fluid from the film fluid.

Both cases described above can typically be found in our daily life. For instance, in a full dishwasher, a jet of water impinges on the surface of some of the plates, overcoming adhesion and cohesion in the material deposited close to the impingement point and thus detaching the droplet from the plate. However, other patches or droplets are covered by a thin draining film which cannot detach them. Therefore, the ability of the film flow to clean the drops of grease or other fouling material through a convective mass transfer is also critical.

In almost all cleaning applications, minimizing the water consumption and the energy of automatic cleaning devices can have an important environmental and sustainable impact. In this study, we investigate the second case presented above where shear forces cannot overcome adhesive and cohesive forces. The drop remains attached onto the surface until it dissolves completely in the film. The time scale of dissolution associated with this case, typically of the order of seconds to minutes, is much longer than the characteristic time scale associated with advection processes in the film flow. The time taken by the film to pass the drop is of the order of 10^{-3}–10^{-1} s, depending on the speed of the film and the length of the drop. Therefore, it is important to study and quantify the impact of the size and shape of a drop, which can be considered as quasi-steady, on the velocity field in the film. In these quasi-steady conditions, we believe it is physically meaningful to model the most viscous droplets as solid obstacles in order to quantify their impact on the film velocity field. A change in the film velocity field can influence the convective mass transfer in a way which is very difficult to predict and assess without a detailed analysis of the complex perturbed flow field.

We are interested in the case of cleaning a single drop of viscous liquid lying on an inclined planar surface using a gravity-driven falling film (see Fig. 1). Blount (2010) develops a mathematical model for the dissolution and transport of the fluid from the drop into the film flow. The streamwise velocity in the film is obtained assuming a viscous–gravity balance and the lubrication approximation,

$$u_\infty(y) = \frac{g \sin\alpha}{2\nu} y(2h_\infty - y), \tag{1}$$

where y is the spatial coordinate in the direction orthogonal to the substrate (x the coordinate in the streamwise direction and z the coordinate in the lateral or spanwise direction), g is the constant of gravity, α is the inclination angle of the substrate from horizontal, ν is the film kinematic viscosity and h_∞ is the far-field film thickness.

The drop fluid (shaded in Fig. 1), considered as a passive tracer, is described using the steady two-dimensional advection–diffusion equation in the diffusive boundary layer in the film phase

$$\boldsymbol{u} \cdot \nabla A = D\nabla^2 A \tag{2}$$

where A is the local concentration of the drop fluid, $\boldsymbol{u} = (u, v, w)$ is the local film velocity and D is the constant diffusion coefficient of the drop fluid in the film phase. Blount (2010) assumes that just outside the drop interface A is fixed, and equal to the maximum solubility A_s of the drop fluid in the film phase, and that the velocity field in the diffusive boundary layer is $u \propto y$. Blount (2010) estimates that the typical thickness of the diffusive boundary layer is smaller than the thickness of the viscous linear sublayer of the momentum boundary layer. Using these assumptions and the lubrication approximation for the diffusive boundary layer, Blount (2010) transforms Eq. (2) into the following partial differential equation, where tildes denote non-dimensional variables (see also Baines and James, 1994 or Bejan, 2013 for more details),

$$\tilde{y}\frac{\partial A}{\partial \tilde{x}} = \frac{\partial^2 A}{\partial \tilde{y}^2}, \tag{3}$$

which has a similarity solution with the similarity variable $\eta = (\tilde{y}^3/\tilde{x})^{1/3}$. Dirichlet boundary conditions are used: $A = A_s$ at the drop surface and A vanishes far away from the interface. Blount (2010) finds the non-dimensional local flux at the interface

$$\tilde{F}(\tilde{x}) \approx 0.539 A_s \tilde{x}^{-1/3}. \tag{4}$$

Blount (2010) obtains the total flux of drop fluid $\bar{F}$, integrated along the drop surface, into the film flow

$$\bar{F} = 0.808 A_s \left(\frac{3g^2 D^6 \Gamma d^6 \sin^2\alpha}{\nu^2}\right)^{1/9}, \tag{5}$$

where Γ is the two-dimensional flow rate and d is the drop length.

Our objective is to test the validity of the model developed by Blount (2010) and compare its prediction with experimental measurements. For simplicity, we focus here on the case of a non-deformable drop, which corresponds to the very viscous limit. One of the main assumptions in Blount's (2010) model is to consider that the film velocity is not affected by the drop and the velocity in the diffusive boundary layer remains linear with distance away from the boundary. This common assumption in theoretical models about the convective mass transfer from a droplet into an external flow is also used by Baines and James (1994) and Danberg (2008). To test this assumption we measure the velocity field of the film flow in