Surfactant spreading on thin viscous films: film thickness evolution and periodic wall stretch

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Abstract

Surfactant spreading on thin viscous films is of interest in the context of surfactant and liquid transport in the lungs, for both normal lung function and treatment of disease, as well as for many industrial processes. This paper presents experimental techniques for the measurement of film deformations due to spreading surfactant and for the investigation of the effects of periodic stretching of the wall supporting the thin film to mimic airway wall motion in the lung due to breathing. Additionally, we present results from both types of experiments, which agree favorably with our theoretical work.

List of symbols

\( \text{Bo} \) Bond number
\( D_s \) surface diffusivity
\( g \) acceleration due to gravity
\( h \) film thickness
\( h_0 \) initial film thickness
\( L_d \) radial position of surface compression disturbance
\( L_0 \) initial radial position of leading edge of new surfactant front
\( L_{\text{new}} \) radial position of new surfactant front
\( p \) pressure
\( Pe \) Péclet number
\( R \) membrane well radius
\( R_0 \) initial membrane well radius
\( \mathcal{R} \) \( R_0/L_0 \), non-dimensional initial membrane well radius (same as cycle average well radius)
\( Re \) Reynolds number
\( t \) time
\( T_C \) stretching cycle period
\( T_{CV} \) ratio of stretch time scale to viscous-surface-tension time scale
\( T_V \) viscous-surface-tension time scale
\( u \) radial velocity
\( U \) viscous-surface-tension velocity scale
\( w \) vertical velocity
\( x \) radial coordinate
\( z \) vertical coordinate
\( \alpha \) shape parameter for initial surfactant distribution
\( \Delta h \) film thickness deformation
\( \Delta x \) horizontal shift in grid position
\( \epsilon \) aspect ratio
\( \Gamma \) surfactant surface concentration
\( \Gamma_0 \) pre-existing surfactant initial surface concentration
\( \Gamma_1 \) new surfactant initial surface concentration
\( \eta \) refractive index of fluid
\( \mu \) viscosity
\( \theta \) angle of incidence
\( \rho \) density
\( \sigma \) surface tension
\( \sigma_{\text{max}} \) maximum surface tension
\( \zeta \) membrane wall coordinate

Superscripts

* indicates dimensional variable (note that dimensional parameters have no asterisk)

1 Introduction

The transport of surfactants on thin viscous films and the resulting film deformations are of concern in the treatment of respiratory distress syndrome (RDS), in which the lungs of prematurely born infants are not developed enough to produce sufficient quantities of surfactant to reduce the surface tension of the lungs’ liquid lining. In surfactant replacement therapy (SRT), surfactant is instilled into the trachea of a patient with surfactant-deficient lungs and it is transported in the large airways primarily by gravity and pressure (Halpern et al. 1998a; Espinosa and Kamm 1999). As the surfactant layer thins to a monolayer, Marangoni flows become the dominant mode of transportation (Halpern et al. 1998a; Espinosa and Kamm 1999). Surface-tension-driven flows are also important in the clearance of liquid and surfactant from healthy lungs (Davis et al. 1974; Espinosa and Kamm 1997; Bull 2000).

Transient spreading of surfactant along a thin viscous film has been studied theoretically (Borgas and Grotberg 1988; Gaver and Grotberg 1990; Troian et al. 1990; Halpern and Grotberg 1992; Jensen and Grotberg 1992; Espinosa et al. 1993; Jensen and Grotberg 1993; Grotberg 1994; Jensen et al. 1994; Shen and Hartland 1994; Grotberg et al. 1995; Bull et al. 1999) and, to a much lesser extent, experimentally (Weh and Linde 1973; Keshgi and Scriven [94]).
1991; Gaver and Grotberg 1992; Bull et al. 1999). When an insoluble surfactant spreads on an otherwise clean thin film, a shock develops near the leading edge of the new surfactant front. A sketch of this is shown in Fig. 1. Figure 1a shows the initially flat film with new surfactant on the left side. When gravity is negligible, the film thickens to twice its undisturbed thickness (Borgas and Grotberg 1988; Gaver and Grotberg 1990; Grotberg 1994) at the shock and thins behind the shock, as shown in Fig. 1b. Thickening of the liquid lining the airways can lead to airway closure, in which a disturbance grows to the point of occluding the airway (Halpern and Grotberg 1993a; 1993b; Halpern et al. 1993; Halpern et al. 1998b; Cassidy et al. 1999; Halpern and Grotberg 1999). Additionally, the film thinning can result in film rupture (Weh and Linde 1973; Keshgi and Scriven 1991; Gaver and Grotberg 1992; Bull et al. 1999), which would halt the spreading of new surfactant and dry underlying tissue, in SRT, unwanted results. There appear to be no other experimental investigations of this film deformation in the current literature. In this paper, we present a constructed-light method for measuring film thickness in surfactant-spreading experiments. This method requires minimal equipment and involves projecting a grid of light onto the film surface to determine the film deformation. Another film deformation involving surfactant, the Reynolds ridge, has been studied extensively (Harper and Dixon 1974; Scott 1982; Warncke et al. 1996). While the mechanism responsible for the production of the Reynolds ridge differs from the mechanism that produces the film deformation in this work (discussed in Sect. 5.1), the experimental techniques used to study the Reynolds ridge

Fig. 1a–d. Schematic of thin film with surfactant, side-view, open square indicates the surface fluid particle that bounds the new surfactant region. The radial location of this position of this particle is $x_{new}^*(t')$. Film thickness, $h'(x', t')$, and surfactant surface concentration, $\Gamma'(x', t')$, evolve as new surfactant spreads. a Initially uniform film with new surfactant and no pre-existing surfactant. b Film disturbance at later time, while new surfactant spreads. c Initially flat film with new surfactant (unfilled) and pre-existing surfactant (filled). d Film at later time. New surfactant has expanded, and pre-existing surfactant is compressed. Location on compression disturbance is indicated by $x_{d}(t')$. 

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