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Drainage of particle stabilized foam film

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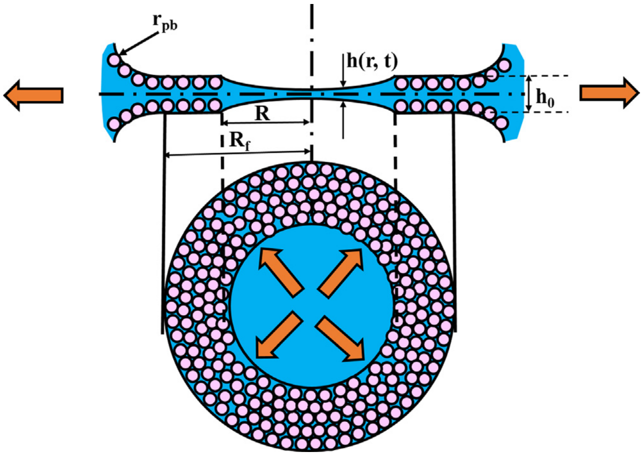
HIGHLIGHTS

- Model for drainage of foam film stabilized by partial particle coverage proposed.
- Lifetime of foam film stabilized by partial coverage of particles characterized.
- Disjoining pressure for film stabilized by close packed particles characterized.
- Maximum disjoining pressure for particle stabilized foam characterized.
- Equilibrium properties of particle stabilized foam characterized.

GRAPHICAL ABSTRACT



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ABSTRACT

A model for drainage of aqueous foam film with a partial coverage of particles accounts for an inner clean air-liquid film surrounded by a film stabilized by close packed particles at the outer periphery. The drainage of the inner film occurs due to capillary pressure gradient. The film thickness is found to decrease fastest at the center with the inner film being thinner than the outer film eventually leading to its rupture as a result of film thickness becoming zero at the center. The velocity of film drainage is found to be higher for lower particle concentration and higher surface tension. The lifetime (time of rupture) of the film is found to be larger for larger bubble size and liquid holdups (higher initial film thickness). For a film stabilized by close packed monolayer or multilayer of particles, the disjoining pressure is larger for larger particle number concentration and particle size, increases with surface tension only for film stabilized by single or two layers of particles and is a function of bubble size only for film stabilized by multilayers of particles. The maximum disjoining pressure decreases with contact angle approaching zero for a critical contact angle of 129° and increases linearly with surface tension. At mechanical equilibrium, the particle stabilized foam gets drier for larger bubble sizes, contact angles and particle number concentrations.

1. Introduction

Particle stabilized foams are encountered in many practical applications such as treatment of radioactive wastes, dispersed sludge, oil-well drilling, pulping in the paper industry, formulation

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Nomenclature

α	Dimensionless surface viscosity
R_b	Radius of the bubble (m)
R_f	Film radius (m)
R	Inner radius of the film which is devoid of particles (m)
h_0	Initial film thickness (m)
r_{pb}	Radius of Plateau border (m)
a	Area occupied by the particle (m^2)
a_p	Area of cross section of Plateau border (m^2)
f^i	Force of interaction for a particle in a film consisting of i (1 or 2) layers of particles
V	Characteristic velocity as defined by Eq. (41) ($m\,s^{-1}$)
V_{init}	Initial velocity of film drainage before the particles are swept to outer periphery ($m\,s^{-1}$)
v_z	Axial velocity in the inner film ($m\,s^{-1}$)
v_r	Radial velocity in the inner film ($m\,s^{-1}$)
v_b	Volume of bubble (m^3)
p	Pressure in the inner film (Pa)
p_{outer}	Pressure in the outer film (Pa)
Δp	Plateau border suction (Pa)
$\Re$	Principal radius of curvature (m)
α	Dimensionless surface viscosity
γ	Surface tension ($N\,m^{-1}$)
t_{init}	Time for particles to be swept to the outer periphery (s)
τ	Characteristic time scale (s)
U_{outer}	Velocity of film drainage in the outer film ($m\,s^{-1}$)
u_z	Axial velocity in the outer film ($m\,s^{-1}$)
u_r	Radial velocity in the outer film ($m\,s^{-1}$)
p_{outer}	Pressure in the outer film (Pa)
ε	Liquid holdup in the foam
ϕ_f	Fraction of liquid in foam that is in film
n_f	Number of films per bubble in the foam
n_p	Number of Plateau borders per bubble in the foam
A_f	Area of the film (m^2)
a_p	Area of cross section of Plateau border (m^2)
D_s	Surface diffusion coefficient of particles at the film interface ($m^2\,s^{-1}$)
l	Length of Plateau border (m)
x_f	Film thickness (m)
h	Film thickness (m)
N	Number of bubbles per unit volume (m^{-3})
N_p	Number of particles in the outer periphery
S	Ratio of surface energy to thermal energy of particle
σ	Particle diameter (m)
θ	Contact angle (radians)
Γ	Particle surface concentration (m^{-2})
Π	Disjoining pressure (Pa)
$g(r)$	Radial distribution function (m^{-1})
$w(r)$	Potential energy of interaction between two bubbles separated by a distance r (J)
$F(r)$	Interparticle force between two bubbles separated by a distance r (N)
$\phi(r)$	Interparticle potential (J)

of many foods etc. The ability of particles to stabilize foams would depend on its wettability to aqueous medium. Pickering [1] was the first to demonstrate that particles that tend to wet water more stabilized O/W emulsions. These particle stabilized emulsions are subsequently referred to as pickering emulsions. The basic mechanism of stabilization by particles is the same in emulsion and foam systems eventhough there are important differences between the two. Detailed reviews of this topic are given elsewhere [2–4]. As one would expect, adsorption of particle onto gas-liquid interface is a prerequisite for stabilization of foam. Therefore, the particle should not be either (i) completely wetted by liquid or (ii) completely repelled by the liquid. In other words, it should have a contact angle between 0 and 180 so that it can reside at the gas-liquid interface. A useful measure of effectiveness of particles in stabilizing foams can be obtained from the energy that is required to detach the particle from the interface. Detailed analysis of the detachment energy for a single [5] and two layers of particles [6] at the interface have been carried out. In these cases, a single or two layers of particles bridge the two faces of the thin film between two neighboring bubbles. Based on the shape of the meniscus between two neighboring particles, expressions have been derived for the maximum capillary pressure needed for the rupture of the thin aqueous film [5,6]. For multiple layer of particles in the aqueous thin film, disjoining depletion forces exist as a result of particle-particle interactions [7]. These forces have been quantified using Ornstein–Zernike theory [8] and step transitions in film thickness as a result has been validated by experimental measurements using reflected light microinterference [7]. However, no quantitative analysis of stability of foam films in the presence of low particle concentrations corresponding to less than monolayer coverage of the interface has been presented. In this manuscript, we present the drainage of thin aqueous foam film between two bubbles that is stabilized by particles. In the first part, we present an analysis for drainage of film stabilized by partial coverage of particles. Expressions for the velocity of film drainage as well as the lifetime of foam film before eventual rupture are presented. Effects of particle concentration, liquid holdup and surface tension on the evolution of shape of thin film for a dodecahedral structure of foam are presented. In the second part, drainage of thin film stabilized by close packed monolayer as well as multilayer of particles was analyzed. Maximum disjoining pressure as well as structure of foam under mechanical equilibrium are quantified.

2. Model for drainage of foam film stabilized by a partial coverage of particles

Schematic of a thin film between two bubbles stabilized by very low particle concentration is shown in Fig. 1. Initially, the particles will be adsorbed at the interface. The air-liquid interface of the film will be covered uniformly by low surface concentration of particles. Since the particle concentration is very low, there will not be any particle present in the bulk (all particles adsorbed). The film will drain due to Plateau border suction. Because of low particle surface concentration, the film interface will be mobile (the interfacial mobility can be described by the surface viscosity μ_s which is higher at larger particle surface concentration). As a result, the particles will be swept to the outer periphery. The velocity of film drainage V_{init} is given by [9],

$$V_{init} = \frac{\Delta p h^3}{4\mu R_f^2}\left[\alpha\left(\frac{h}{R_f}\right)\sum_{n=1}^{\infty}\frac{\lambda_n^2 J_2(\lambda_n)}{\left(1+\alpha\left(h/R_f\right)\lambda_n^2\right)\lambda_n^3 J_1(\lambda_n)}\right]^{-1} \tag{1}$$

where $\alpha = \mu_s/\mu R_f$ is the dimensionless surface viscosity, $J_0(\lambda_n) = 0, n = 1, 2\ldots$ and $\Delta p = \gamma/r_{pb}$ is the Plateau border suction. The radial velocity at the periphery of the film $V_{R,init} = V_{init} R_f/2h$ The timescale t_{init} for sweeping of the particles to the periphery is given by $t_{init} = R/V_{R,init}$. Therefore,

$$\frac{t_{init}}{\tau} = \alpha\left(\frac{h}{R_f}\right)\sum_{n=1}^{\infty}\frac{\lambda_n^2 J_2(\lambda_n)}{\left(1+\alpha\left(h/R_f\right)\lambda_n^2\right)\lambda_n^3 J_1(\lambda_n)} \tag{2}$$

In the above equation, τ is the characteristic time scale which is defined later in Eq. (4). Because of low particle surface con-