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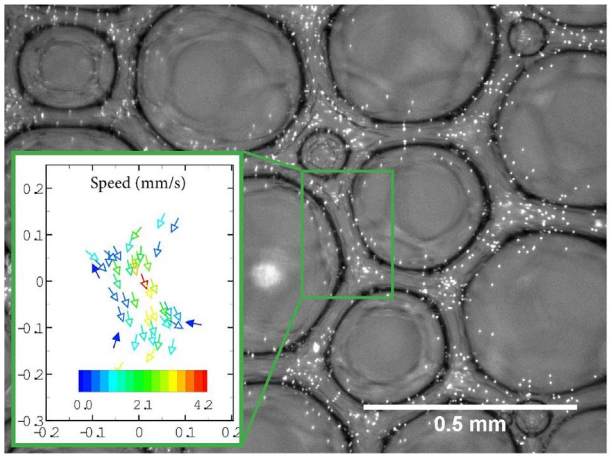
Velocimetry of interstitial flow in freely draining foam

Matthew J. Kennedy[a], Michael W. Conroy[b], James W. Fleming[b,c], Ramagopal Ananth[d,*]

[a] Former National Research Council Associate at the Naval Research Laboratory, Washington, DC 20375, USA
[b] Formerly at Naval Research Laboratory, Chemistry Division, 4555 Overlook Ave., SW, Washington, DC 20375, USA
[c] Senior Staff Scientist, Nova Research Inc., 1900 Elkin Street, Suite 230, Alexandria, VA 22308, USA
[d] Naval Research Laboratory, Chemistry Division, 4555 Overlook Ave., SW, Washington, DC 20375, USA

GRAPHICAL ABSTRACT



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ABSTRACT

Interstitial flows at the middle height of a freely draining foam column were measured by microparticle image velocimetry (μPIV), and superficial flow was measured from the bottom of the foam by a digital weighing scale. In addition, Plateau border widths were measured from the μPIV images. Plateau borders were selected for μPIV particle-tracking analysis based on their orientation being nearly vertical. Interstitial liquid velocity in the vertically oriented Plateau borders was found to depend linearly on the square of the width consistent with Poiseuille flow. Three foams were examined including a commercial fluorinated Aqueous Film Forming Foam (AFFF), a commercial non-fluorinated firefighting foam (Re-healing Foam Type 6; RF6), and a simple lab-mixed foam composed from sodium dodecyl sulfate (SDS) in water. The interstitial velocity and superficial velocity measurements were compared with theoretical models that assumed either channel-dominated (CD) or node-dominated (ND) viscous dissipation, *i.e.* rigid or mobile interfaces. The measurements were found to fall in between the two limiting cases for AFFF and RF6, with RF6 showing closer agreement with the CD case than the ND case. Flow measurements in SDS foam agreed approximately with the ND model, as expected, prior to foam breakdown. An approximate liquid volume fraction at the middle height of the foam column was also obtained from the ratio of interstitial flow to superficial flow.

* Corresponding author.
E-mail address: ramagopal.ananth@nrl.navy.mil (R. Ananth).

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1. Introduction

Interstitial flow in foam takes place within the liquid-filled channels, *i.e.* the Plateau borders (PBs). Superficial flow is the average flow of liquid through a cross-section of the foam. In most theoretical foam drainage models, the superficial flow is assumed to be directly proportional to the interstitial flow by a geometric scaling factor [1–3]. Scaling is often based on a unit cell geometry that may be used to model the foam, for example a tetrakaidecahedron [1].

Micro particle image velocimetry (μPIV) is an optical technique to measure velocity at the micro-meter scale and is used to measure drainage in a PB. The present work extends previous μPIV studies on forced drainage experiments [4–6] in foams by examining free drainage for the first time. In forced drainage, liquid is continuously supplied at the top of the foam to replenish the liquid lost by drainage, so that the rate of injection determines the drainage at steady state. In free drainage, liquid is not forced through the foam to replenish the loss, so the flow is time dependent. In the forced drainage experiments, the liquid volume fraction is limited to an approximate range of $0.001 < \alpha < 0.1$ [2], since slow injection of liquid gives a broadening wavefront due to hydrodynamic dispersion [1], and fast injection of liquid makes the gas bubbles become buoyant [7]. In practice, a firefighting foam is typically delivered initially wet (initial liquid volume fraction $\alpha_0 > 0.1$) and then becomes dry ($\alpha \leq 0.01$) due to the dynamics of liquid loss by drainage. Therefore, firefighting foams are investigated in the context of free drainage dynamics.

Viscous dissipation is a key parameter in foam drainage theory. In the context of two limiting behaviors, most theoretical models consider two primary mechanisms of viscous dissipation [8]: shear resistance at the walls of the Plateau borders, and bottlenecking of the flow at the nodes. Assumption of rigid walls gives Poiseuille flow in the Plateau borders leading to channel-dominated (CD) drainage. Assumption of fully mobile walls gives plug flow in the Plateau borders leading to node-dominated (ND) drainage [4–6]. Early theoretical modeling studies on foam drainage mostly used CD models [9–13], but researchers have increasingly used ND models [1,2,14,15] since their first description by Koehler et al. in 1999 [1]. Foams generated using small surfactant molecules, like sodium dodecyl sulfate (SDS, MW = 288 g/mol), are now modeled mostly as ND foams while foams generated using large surfactant molecules, like casein protein (MW = 20,000 g/mol), are often modeled as CD foams [3]. However, little is known about the viscous dissipation behavior of commercial firefighting foams.

Some of the Firefighting foams that are used to fight liquid pool fires contain fluorocarbon surfactants as a key ingredient and are called Aqueous Film Forming Foams (AFFFs). The perfluorocarbon surfactant's tail is oleophobic unlike the oleophilic tail of a hydrocarbon surfactant potentially influencing the liquid drainage behavior in the foam. Another difference is that the surface tension of AFFF solution is extremely low compared to RF6 (Rehealing Foam, Solberg Inc.) and SDS solutions that can affect the capillary force and drainage. AFFFs are uniquely able to blanket and smother fires on liquid pools of hydrocarbon fuel. Non-fluorinated alternatives to AFFF have recently come under development in response to concerns about suspected bioaccumulation of certain perfluorocarbons in the environment. Fluorine-free firefighting foams (e.g., RF6, August 2005, Solberg Inc.,) have included non-Newtonian viscosifiers as additives to the hydrocarbon surfactant solution to make it highly viscous and slower draining. But, the fluorine-free foams have been unable to match the fire suppression performance of AFFF. The differences in the effects of fluorocarbon surfactants, hydrocarbon surfactants, and various additives contained in commercial firefighting foam solutions on the flow are not well understood.

In the present paper, μPIV measurements of interstitial flow velocity at the middle height of the foam and weighing scale measurements of superficial flow velocity at the bottom of the foam are compared with theoretical models of foam drainage. The models consider alternate modes of viscous dissipation, namely CD and ND flow as the two limiting behaviors where flows measured experimentally are expected to fall in between. Differences in fluorocarbon and hydrocarbon surfactants contained in the foams are seen to affect both the decrease in collective (superficial) flow and the individual (interstitial) flow with time. The data provide insight into the differences in liquid drainage dynamics between fluorocarbon and fluorine-free aqueous foams and reflect the effects of specific ingredients, like fluorocarbon surfactants and viscosifiers. Understanding liquid drainage among different foams is important because liquid drainage affects water content of the foams, which can affect foam spread on burning liquid pools and the fire suppression.

2. Numerical analysis

2.1. Foam drainage theory

We have applied theoretical models to predict free drainage in firefighting foams and discuss them within the context of model assumptions. We selected theoretical models for CD and ND drainage in foam that followed primarily those presented in Koehler et al. [14].

We considered liquid drainage through a bed of mono-dispersed bubbles of diameter D_B and bed height H. We set $z = 0$ at the bottom of the foam, and we took $+\hat{z}$ in the opposite direction as gravity.

Mass conservation of liquid gives [14]

$$\frac{\partial \alpha}{\partial t} + \vec{\nabla} \cdot (\alpha \vec{u}) = 0 \tag{1}$$

where $\vec{u}$ is the local velocity of the liquid, and α is the local liquid volume fraction. "Local" quantities are values that are averaged across a small volume containing few bubbles in three-dimensional space typical of multiphase flow analyses. Darcy's law for porous media relates gravity g, pressure gradient $\vec{\nabla} p$, and permeability k of the foam to the local velocity through the medium [14]:

$$\vec{u} = \frac{k}{\mu}(\rho \vec{g} - \vec{\nabla} p) \tag{2}$$

where μ is the dynamic liquid viscosity and ρ is the liquid mass density. The pressure gradient due to capillary pressure follows from the Laplace-Young equation:

$$p = p_{gas} - \gamma / r \tag{3}$$

where γ is the surface tension of the liquid, p_{gas} is the gas pressure assumed to be the same in all bubbles since a monodisperse size distribution is assumed, and r is the radius of curvature of the gas-liquid interface. For liquid volume fraction $\alpha \leq 0.1$, the radius of curvature may be approximated as follows:

$$r \approx \delta_\alpha^{-1/2} L \alpha^{1/2} \tag{4}$$

where $\delta_\alpha \approx 0.1711$ for a monodisperse tetrakaidecahedra [1], and L is the edge length of regular tetrakaidecahedral bubbles in a Kelvin foam, which is given by $L = 0.408 D_b$, where D_b is the bubble diameter. Substituting Eq. (4) into Eq. (3) gives $\nabla p = -\gamma \delta_\alpha^{1/2} L^{-1} \nabla(\alpha^{-1/2})$, which combined with Eq. (2) gives the local liquid velocity as:

$$\vec{u} = \frac{k}{\mu}(\rho \vec{g} + \gamma \delta_\alpha^{1/2} L^{-1} \nabla(\alpha^{-1/2})) \tag{5}$$

Combining this with Eq. (1) gives the generalized foam drainage equation (Eq. (7) from Koehler et al. [14]):

$$\frac{\partial \alpha}{\partial t} + \frac{1}{\mu}[\rho \vec{g} \cdot \vec{\nabla}(\alpha k) - \gamma \delta_\alpha^{1/2} L^{-1} \vec{\nabla} \cdot (k \vec{\nabla}(\alpha^{1/2}))] = 0 \tag{6}$$

where k is a function of α and L and the negative sign in the last term arose from use of the identity $f \partial f^{-1/2} / \partial x = -\partial f^{1/2} / \partial x$.