FOAM DRAINAGE ON THE MICROSCALE

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Summary Although foam drainage occurs on the microscale, i.e. the level of individual channels and nodes, most experiments have been performed on the macroscopic scale at the level of many bubbles. Various different mean-field models have been developed which differ in their assumptions of the fluid flow on the microscale, which until recently could not be verified. Novel foam drainage experiments on the scale of individual channels are presented, which confirm the model of Leonard and Lemlich [1], that the surface viscosity sets the interfacial mobility. Analytical solutions for the flow rates through the channels are given, which are a key ingredient for developing a complete macroscopic description of foam drainage.

INTRODUCTION

Foam drainage is known as the process of fluid flowing out of (liquid) foams, which generally is driven by gravity, and results in overall removal of liquid from the foam. On a macroscopic level, on the scale of many bubbles, this process can be characterized by an average liquid velocity and a liquid volume fraction, which is the relative density of the foam. Experiments show that the relationship between the mean velocity and liquid volume fraction depends on the type of surfactant used to stabilize the foam as well as the size of the bubbles that comprise the foam. Thus a simple power-law dependence of the liquid velocity and liquid volume fraction cannot adequately capture the rich dynamics of foam drainage [2, 3, 4, 5].

Obviously macroscopic foam drainage depends on the microscopic details of how liquid flows through the continuous fluid network that is the interstitial region between the bubbles. The fluid network consists of films, which are the regions between adjacent bubbles, channels, which are long and slender triangular regions between three neighboring bubbles, and nodes, which are the junctions of four channels. Experiments using confocal microscopy to determine the flow fields inside individual channels show the effects of the surfactant. The microscopic flow fields can be quantitatively described using an earlier model developed by Leonard and Lemlich [1], which takes into consideration the surface viscosity due to the surfactants that stabilize the foam. This in turn suggests how a macroscopic model can be developed to account for dependence of bubble size and surface viscosity on the the average velocity of the liquid flowing between the bubbles of the foam.

ELEMENTARY MODELS

A minimal model to describe the drainage dynamics is a modification of Darcy's law for flow through porous media. The liquid's velocity through porous media, such as sandstone, depends on the effective cross-sectional area of the channels for fluid flow, which is known as the permeability k, the fluid viscosity, μ, and the gravitational driving force, ρg:

$$\mu v = k\rho g \ . \tag{1}$$

For monodisperse foams, the average cross-sectional area of the channels is proportional to L^2 and increases almost linearly with the liquid volume fraction, ϵ, provided the liquid volume fraction is small [6]. Thus the the foam drainage velocity is

$$v = L^2 \epsilon^{\chi} \rho g/\mu \ , \tag{2}$$

where the exponent $\chi \approx 1$ [3, 7].

However experiments showed that the drainage velocity has a much more complicated dependence on the liquid volume fraction than given by equation (2). The following trends were observed:

1. For soap foams, (such as SDS or CTAB), in the limit of small bubbles where $L \ll 1$ mm, the fitting exponent approaches one from below, $\chi \nearrow 1$, whereas for foams with large bubbles, $L \gtrsim 1$ mm, the fitting exponent approaches one half from above, $\chi \searrow 1/2$.

2. For foams stabilized with protein surfactants the exponent is fairly close to $\chi \approx 1$. Likewise for foams stabilized with a mixture of SDS and dodecanol, the best fit for the exponent of equation (2) is $\chi \approx 1$ [8].

Thus it is necessary to include a further material parameter in an improved model for foam drainage, to account for the dependence of the fitting exponent on the type of surfactant used. Also another length scale must be included in the model to account for the variation of $\chi(L)$ (see first point above).

THE ROLE OF SURFACE VISCOSITY

In 1967 Leonard and Lemlich proposed a model for foam fractionation that includes the surface viscosity, μ_s, which is a two-dimensional viscosity [9]. The surface viscosity is a material parameter of the surfactant that depends on the size of the surfactant molecules as well as the interactions between the surfactant molecules. According to this model, foams made with surfactants having large surface viscosities, rigidify the liquid-air interfaces, and produce Poiseuille-like flow fields in the channels. On the other hand, foams made with surfactants that have low surface viscosities give rise to mobile interfaces which produce flow fields that are more like plug-flow. The Boussinesq number is $Bo \equiv \mu_s/\mu L$ is a dimensionless parameter characterizing the rigidity of the interfaces due to the surface viscosity. Thus fine foams (small L) and foams with large surface viscosities both have the large Boussinesq numbers, which qualitatively agrees with the experimentally observed trends that $\chi \nearrow 1$ reported above. On the other hand SDS foams with large bubbles have small Boussinesq numbers, and relatively mobile interfaces, which gives different drainage dynamics.

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A novel method for measuring liquid velocities through individual channels inside a foam involves confocal microscopy, and tracer particles [10]. Until recently all experiments were conducted on the macroscopic scale, and the details of the actual flow were unknown, although every model for foam drainage involved assumptions for the microscopic flow fields in the channels.

Confocal experiments were performed on different foams made with different surfactants. Velocity profiles were obtained of axial cross-sections of individual channels, in the direction of the flow. The results confirm that foams made with different types of surfactants have different flow fields. Furthermore, the measured velocity profiles agree well with the Leonard and Lemlich model, that takes into account the mobility of the faces which is set by the surface viscosity.

A recent accomplishment was to develop simple analytical formulas to estimate the average flow rates through certain types of individual members of the fluid network of a foam [11]. For a long and slender channel of width a [12], surface viscosity μ_s, and pressure gradient G that drives the flow, a simple formula for the flow rate is

$$\langle q_{\text{channel}} \rangle \approx \left(\frac{Ga^4}{6\mu}\right)\left(\sqrt{3}-\pi/2\right)^2 \left\{\sqrt{\frac{2\mu a}{\mu_s}}\arctan\left(\sqrt{\frac{\mu a}{8\mu_s}}\right) - \arctan\left(\frac{\mu a}{2\pi\mu_s}\right) + 3/25\right\} . \quad (3)$$

Generally the flow rate through the films is small, so the only remaining important network elements for the flow are the nodes. However modelling and measuring the flow fields of nodes so far has not been accomplished.

CONCLUSIONS AND OUTLOOK

The dynamics of foam drainage are complex, and even for simple aqueous foams still remain poorly understood. Recent experiments have revealed how liquid flows through individual channels, and these flows are in good agreement with Leonard and Lemlich's model. However the liquid also flows through nodes, where the four channels intersect, and the details of the flow through the nodes remain to be determined. Once the flow fields through nodes is better understood, it should be possible to take into account the role of both nodes and channels and create a complete model for foam drainage.

References

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