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Drainage of Meringue Mixture Froth

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ABSTRACT

The drainage of meringue mixture froth is considered. The mixture exhibits shear-thinning rheology that can be approximately described by the Cross model for pseudo-plastic fluids. However, strain rates in the draining meringue foam are low so the drainage through the Plateau borders may be approximated by assuming that the mixture exhibits Newtonian rheology and has viscosity given by the Cross model at zero strain rate. This has been proven by numerically calculating the drainage rate of the shear-thinning fluid within Plateau borders using a finite element code and comparing it to the drainage rate calculated for a Newtonian fluid. The surface shear viscosity was measured and is found to be non-Newtonian. Even though the surface shear viscosity is relatively high, the high bulk viscosity causes the Boussinesq number to be low and therefore the predicted drainage rate is significantly greater than would be seen if the Plateau border walls were infinitely rigid. Drainage profiles are obtained using magnetic resonance imaging; in a future work these will be compared to models for drainage of an egg white froth that take into account the rheological considerations that have been discussed herein.

INTRODUCTION

The drainage of interstitial fluid from foam has been the subject of intensive research. The existing work has concentrated upon foams that have interstitial liquid exhibiting Newtonian rheology. Moreover, investigators who have considered the drainage of egg-white froths (which is shear-thinning) have assumed Newtonian rheology for the interstitial liquid [1]. Knowledge of the drainage of non-Newtonian fluids through froths is of interest not only to the baking industry who use, for example, mixtures of egg-white and icing sugar to create foams in the production of meringue, but to those designing froth flotation operations where hydrophilic particles in the interstitial liquid form a non-Newtonian slurry [2]. As a preliminary to modeling the drainage of meringue mixtures, we calculate the drainage rate for a Cross-fluid draining in a vertical Plateau border since it is shown that the interstitial liquid exhibits rheology similar to a pseudo-plastic. Also presented are preliminary foam drainage data taken using magnetic resonance imaging that will be compared against a model for foam drainage that takes into account the rheological considerations discussed herein in a future work.

EXPERIMENTAL

The meringue mixture was made by mixing 1 part (by mass) dehydrated egg white (Henningsen Foods product P-110) to 5 parts icing sugar and 7 parts de-ionised water. The mixture was placed in a 100 g glass jar, shaken vigorously by hand and placed in a Bruker DMX 200 magnetic resonance spectrometer operating at a proton (^{1}H) frequency of 199.7 MHz. One-dimensional axial (Z) profiles were acquired at two second intervals using a standard one-dimensional spin-echo profiling pulse sequence. The field of view was 100 mm and 256 data points were acquired giving a spatial resolution of 390 μm. Signal losses due to spin-lattice T_1 relaxation losses were calculated to be negligible and those due to T_2 losses were corrected for. In addition, all one-dimensional profiles were corrected for B_1 radiofrequency inhomogeneities by dividing the experimental profiles by those obtained under identical conditions, of a pure water phantom. Full experimental details are further results will appear in a forthcoming publication. The steady shear viscosity of the mixture and the frequency response at 10 % strain were measured on an Advanced Rheometric Expansion System and are shown in Figures 2 and 3.

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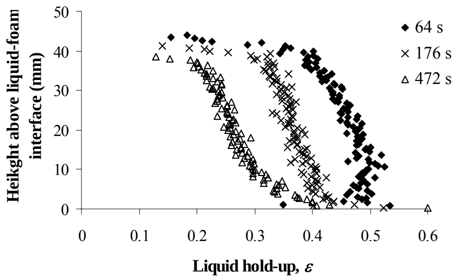

Figure 1. Drainage profiles for the egg /sugar froth.

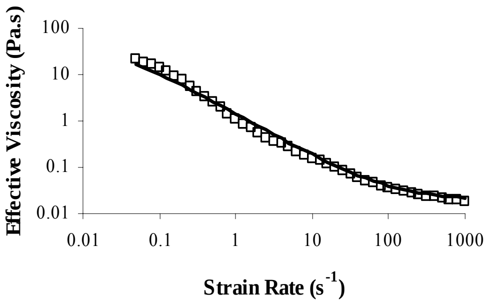

Figure 2. Steady shear viscosity versus strain rate with Cross model (solid line) superimposed.

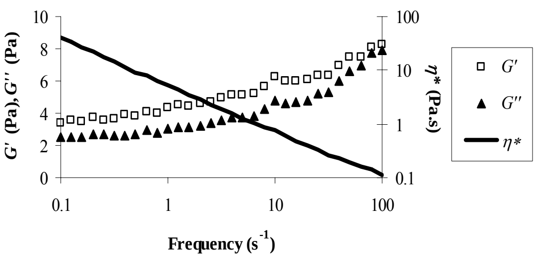

Figure 3. Storage G' and loss G" moduli for the interstitial fluid with complex viscosity.

The steady shear viscosity, μ, can be approximately described using the Cross model for pseudo-plastic fluids [3] as a function of plane strain rate thus:

$$\mu \approx \frac{54}{1+\left(50\dot{\gamma}\right)^{0.93}}+0.02 \tag{2}$$

It is pertinent to estimate the characteristic frequency of strain in a draining froth by calculating the reciprocal of the residence time in the Plateau border. The length of the Plateau border, L, can be calculated using [4]:

$$L \approx 0.718\frac{r_b}{\left(1-\varepsilon\right)^{1/3}} \tag{3}$$

In the experiments reported herein the harmonic mean bubble radius, r_b, was 21 μm so, for a froth of liquid fraction, ε, of 40%, L is approximately 17 μm. The density of the mixture is 1240 kg.m^{-3}. The numerically calculated velocity in a vertical Plateau border for a 40% liquid fraction meringue foam is 0.2269 nm.s^{-1} (the modeling is described below). Thus the characteristic frequency of flow through a network of Plateau borders is about 10^{-4} Hz so the flow can be considered pseudo-steady. Surface shear viscosity, Figure 4, has been measured using a CIR-100 Interfacial Rheometer; it is seen that the surface shear viscosity is non-Newtonian.

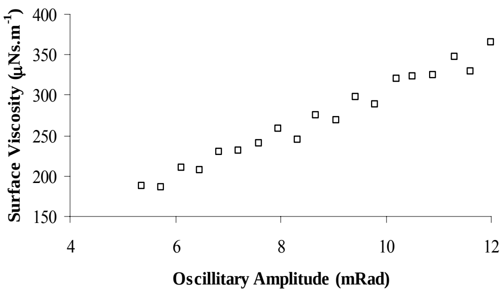

Figure 4. Surface viscosity versus oscillatory amplitude for mixture at 3 Hz.

MODELLING AND DISCUSSION

The cross sectional area of the Plateau border is taken to have six-fold symmetry (see Figure 5).

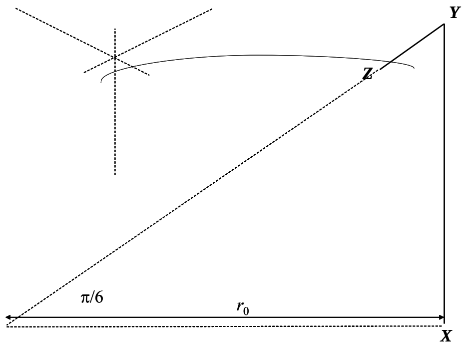

Figure 5. Schematic of cross section of Plateau border and co-ordinate frame. r_0 is the radius of curvature of the Plateau border walls. The cross section is formed from the void between three mutually contacting cylinders.

The Navier-Stokes equation for a vertical channel, neglecting inertial and temporal components and recognizing that the term ∇p is small compared to the gravitational term, is:

$$\mu\nabla^2 u + \rho g = 0 \qquad (4)$$

which is Poisson's equation. Here viscosity is a function of the second invariance of the deformation rate tensor E, ie.

$$\dot{\gamma} = \sqrt{2E_{ij}.E_{ij}} \qquad (5)$$

so that the constitutive equation satisfies material objectivity and coordinate invariance principles. This is solved using the Fastflo (CSIRO, Australia) finite element code subject to the following boundary conditions:

$$u = 0 \quad \text{on } ZX \text{ (no-slip)} \qquad (6)$$

$$\underline{n}.\nabla u = 0 \quad \text{on } XY \text{ and } YZ \text{ (symmetry)} \qquad (7)$$

where $\underline{n}$ is the unit vector normal to the boundary of the solution domain. The efficacy of the numerical technique was tested by comparing solutions for the flow of a Newtonian liquid to those previously reported in the literature. The numerically calculated superficial velocity in a vertical Plateau border (given above) is 0.2269 nm.s^{-1}. This may be compared to the value of the superficial velocity, j, of a Newtonian fluid of viscosity 54.02 Pa.s (i.e. the viscosity at zero strain for the Cross model to the meringue mixture liquid) that is calculated using [2]:

$$j = \frac{\rho g A}{50.1\mu} \qquad (8)$$

where A is the cross-sectional area of the Plateau borders. The calculated superficial velocity j is 0.2259 nm.s^{-1} which corresponds closely to the results gained by finite element simulation for the flow of a pseudo-plastic fluid. It is therefore apparent that the drainage of a meringue froth may be effected by considering the interstitial liquid to exhibit Newtonian viscosity taken at the limit of zero strain rate. This suggestion is in contrast to [1] where the drainage of an egg white froth was measured; the interstitial liquid was considered Newtonian and the viscosity appears to have been measured at a plane strain rate of around 1000 s^{-1}.

In the numerical simulations and the development of Eq. 8 it is assumed that the walls of the Plateau borders are rigid (i.e. there is an infinite surface shear viscosity). In fact as can be seen in Figure 4, the surface shear viscosity is finite (and is non-Newtonian). This has the effect of enhancing drainage rate as the condition of no-slip at the wall of the Plateau borders is no longer valid. The velocity profile of a Newtonian fluid flowing in a Plateau border of finite surface shear viscosity has been calculated [5]. Thus a drainage enhancement factor, χ, may be proposed:

$$\chi = 50\left(\frac{0.065Bo^{-0.5}}{0.209 + Bo^{0.628}} + 0.02\right) \qquad (9)$$

where $Bo \equiv \mu_S / \mu r_0$ is the Boussinesq number based upon the Plateau border radius of curvature and μ_S is the surface shear viscosity. If we assume a constant surface shear viscosity of 250 μNs.m^{-1} then in the ε=40% case, Bo==0.26 and χ=10.9. Therefore the drainage rate through a Plateau border is approximately 10.9 times greater than predicted in Eq. 8 which is significant. The reason such large drainage enhancement is that, even though the surface shear viscosity is relatively high, the bulk liquid velocity is very large in the limit of zero strain rate and therefore the Boussinesq number is low.

SUMMARY

Nuclear magnetic resonance imaging results for the drainage of meringue mixture froth have been presented. The mixture exhibits shear-thinning rheology that can be approximately described by the Cross model for pseudo-plastic fluids. However, strain rates in the draining foam are low so the drainage through the Plateau borders may be approximated by assuming that the mixture exhibits Newtonian rheology and has viscosity given by the Cross model at zero strain rate. Even though the surface shear viscosity of the mixture is relatively high, significant enhancement of drainage through Plateau borders is expected because the bulk viscosity is high leading to a relatively low Boussinesq number. These rheological considerations will be employed to try to model the drainage process and compare the model to the NMRI results in a future work,

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