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Comparison of the rheology of bubbly liquids prepared by whisking air into a viscous liquid (honey) and a shear-thinning liquid (guar gum solutions)

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ABSTRACT

Many bubbly liquids found in food applications feature non-Newtonian liquid phases whereas most investigations of bubbly liquid rheology have employed Newtonian liquids as the continuous phase. The influence of the nature of the continuous phase on bubbly liquid rheology was investigated using bubbly liquids prepared in the same planetary mixer using a viscous liquid, honey (almost constant shear viscosity with a small elastic contribution) and a shear-thinning liquid (1 wt% aqueous solution of guar gum). The viscosity of the honey was similar to the low-shear-rate limit viscosity of the guar gum solution. Although similar bubble volume fractions (up to 25%) were entrained in each liquid under identical mixing conditions, the bubble diameters in the shear-thinning liquid were about two to three times larger than those in the honey. Introduction of a surfactant into the shear-thinning liquid increased the volume fraction of bubbles to approx. 40% and further increased the size of the bubbles. The presence of the bubbles in the honey caused it to become shear-thinning, to exhibit noticeable elastic effects and exert significant normal stress differences. The honey-based bubbly liquids exhibited many of the features in the simulations of Loewenberg and Hinch (1996) and fitted the model of Llewellin et al. (2002) well. In the guar gum solution, these characteristics, already present, were accentuated strongly by the presence of the bubbles. Subjecting both types of bubbly liquids to high shear rates caused the volume fraction of bubbles to decrease and made the bubbly liquids less shear-thinning. Noticeable thixotropy was observed. Shear-thinning, associated with bubble deformation, was observed at lower values of the relative shear stress in the shear-thinning liquid.

1. Introduction

Bubbly liquids are dispersions of bubbles in a liquid, with bubble volume fractions typically ranging up to 50%. The continuous liquid phase is usually viscous, retarding coalescence and creaming. In the food sector, the bubble phase is usually air and aerated foods are ubiquitous, from beverages to baked products, ice creams, dairy systems and confectionery, e.g. Campbell and Mougeot (1999). Aeration yields a softer texture, increased spreadability, a more homogeneous appearance and a more uniform distribution of taste (Thakur et al., 2003). Aerated foods are appreciated by the consumer for the particular texture that the air, entrapped as small cells, imparts to them. Moreover, air cells can be used to replace fats in low-calorie products and healthier foods (Gabriele et al., 2012). Bubbly liquids are also encountered in nature in the form of magmas (Manga and Loewenberg, 2001) and in other industrial sectors in the form of cement (Ahmed et al., 2009), extracted crude oil (Abivin et al., 2009), cosmetics and personal care products (Malysa and Lunkenheimer, 2008).

The presence of the bubble phase modifies the rheology of the liquid, giving rise to shear-thinning and viscoelastic behaviour. In steady shear, at low shear rates the bubbles resist deformation and the behaviour resembles that of suspensions, with relative viscosity increasing with bubble volume fraction, ϕ. At higher shear rates, bubble deformation occurs, promoting alignment with the flow and giving rise to shear-thinning. The transition to shear-thinning behaviour in bubbly liquids and emulsions is usually discussed in terms of the capillary number, Ca, which compares the deforming stresses from fluid shear to the restoring capillary pressure:

$$Ca = \frac{\eta_0 \dot{\gamma} r}{\Gamma} \tag{1}$$

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Nomenclature

Roman

a	fitting parameter, Szyszkowski equation, N m^{-1}
a'	dimensionless parameter, –
a_1, a_2	parameters, Eq. (17), –
b	fitting parameter of Szyszkowski equation, mol dm^{-3}
b'	dimensionless parameter, –
C	concentration, mol dm^{-3}
Ca	capillary number, –
$d_{\max}$	largest measured bubble diameter, m
$d_{\min}$	smallest measured bubble diameter, m
F_{normal}	normal force generated by the flow between plates, N
k	time constant, s^{1-n}
K	dimensionless parameter, –
G'	storage modulus, Pa s
G''	loss modulus, Pa s
n	flow index, –
n_b	number of bubbles, –
N_1	first normal stress difference, Pa
N_2	second normal stress difference, Pa
N_c	number of classes of bubbles, –
r	radius of the undeformed bubble, m
R_{pp}	radius of parallel plate geometry, m
R^2	square of the correlation coefficient, –
T	torque, N m
w	class interval width, m
Wi	Weissenberg number, –
x	variable, Eq. (17), –

Greek

α_1	parameter, Eq. (3), s
β_1	parameter, Eq. (3), Pa s
β_2	parameter, Eq. (3), Pa s^2
δ	phase shift, degrees
ϕ	air volume fraction, –
$\dot{\gamma}$	shear rate, s^{-1}
$\dot{\gamma}_R$	shear rate experienced at the rim of the parallel plates, s^{-1}
Γ	surface tension between liquid phase and the air, N m^{-1}
Γ_0	surface tension between the solvent and air, N m^{-1}
η_{app}	apparent viscosity, Pa s
η_0	zero-shear-rate viscosity, Pa s
η_r	relative viscosity, –
η'	real component of the complex viscosity, Pa s
η''	imaginary component of the complex viscosity, Pa s
$\lvert\eta^*\rvert$	magnitude of the complex viscosity, Pa s
λ	relaxation time, s
ρ_s	density, kg m^{-3}
ρ_{us}	density of deaerated sample, kg m^{-3}
τ	shear stress, Pa
τ^*	dimensionless shear stress, –
τ^*_{CR}	critical dimensionless shear stress, –
ω	angular frequency, Hz
Ω	rotational velocity, rad s^{-1}

where η_0 is the viscosity of the continuous liquid phase, $\dot{\gamma}$ is the imposed shear rate, r is the radius of the undeformed bubble, and Γ is the liquid-bubble interfacial tension. When Ca is large, the deforming force (given by the shear stress in the continuous phase, $\eta_0\,\dot{\gamma}$) is large compared to the restoring force (related to the capillary pressure in the bubble, $\sim 2\Gamma/r$), and the bubbles are deformed, resulting in shear-thinning. At high shear rates the relative viscosity, η_r (defined as the ratio of the apparent viscosity of the aerated sample to the viscosity of the continuous phase), approaches the Voight average, $1-\phi$ (Manga and Loewenberg, 2001). Experimental and modelling studies of shear flow and bubble shape interactions have been reported by several workers, e.g. Manga and Loewenberg (2001); Loewenberg and Hinch (1996); Thompson et al. (2001); Müller-Fischer et al. (2008). Many of the studies in this area are principally concerned with emulsions: bubbly liquids represent a limiting case where the ratio of the viscosity of the dispersed phase to the continuous phase is small and where the large difference in densities allows the dispersed entities to change shape rapidly (i.e. little inertia).

Much of the prior work has considered isolated bubbles or dilute systems, whereas many bubbly liquids of interest involve moderate or high bubble loadings. Bubble crowding then affects the shear stress experienced by individual bubbles and workers such as Golemanov et al. (2008) have advocated the use of the effective medium approach employed in dense suspensions to describe effect of shear stress in foams and concentrated emulsions. The capillary number is then replaced by the dimensionless shear stress, τ^*, defined as:

$$\tau^* = \frac{\tau}{\Gamma/r} \tag{2}$$

which for a single bubble in a Newtonian liquid is equivalent to Ca. Golemanov et al. reported a critical value for droplet break-up, $\tau_{CR}{}^*$, of $\sim$0.40 for foams with $\phi \sim 0.92$ and a lower value of 0.15 for hexadecane-in-water emulsions with $0.83 < \phi < 0.95$. These values were orders of magnitude lower than those expected for single droplets in sheared Newtonian liquids.

Llewellin et al. (2002) provided a good review of the pertinent literature as part of their paper presenting a model for bubbly liquid rheology under steady and oscillatory shear conditions. They performed experiments using golden syrup as the continuous phase with air volume fractions up to 0.5 and reported bubble crowding effects in steady shear measurements. They also conducted oscillatory shear tests and reported noticeable viscoelastic effects arising from the presence of the bubble phase which could be described reasonably well by a modified linearised Frankel and Acrivos model (Frankel and Acrivos, 1970). They reported two forms of the model: (i) a monodisperse model, based on a single characteristic bubble size to account for all the bubbles in the liquid and (ii) a polydisperse model, involving the bubble size distribution. The latter applies the monodisperse model to each bubble size fraction and calculates the overall response as the sum of the individual monodisperse contribution for each size classes weighted by the contribution of each size fraction to the total bubble volume fraction, ϕ.

In the Llewellin et al. model the real and imaginary parts of the complex viscosity, η' and η'', respectively, are given by:

$$\eta' = \frac{\beta_1 + \alpha_1\beta_2\omega^2}{1+\alpha_1^2\omega^2} \tag{3}$$

$$\eta'' = \frac{(\beta_1\alpha_1 - \beta_2)\omega}{1+\alpha_1^2\omega^2} \tag{4}$$

where ω is the angular frequency. The coefficient α_1 is calculated from

$$\alpha_1 = \frac{6}{5}\lambda, \tag{5}$$

where λ is the deformation time scale, given by