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Effect of bubble volume fraction on the shear and extensional rheology of bubbly liquids based on guar gum (a Giesekus fluid) as continuous phase

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ABSTRACT

The effect of air bubble volume fraction, ϕ, on the steady shear and extensional rheology of aqueous guar gum solutions was studied at $0 \leqslant \phi \leqslant 0.25$ and gum concentrations of (i) 5 g/L and (ii) 10 g/L, corresponding to solutions in the (i) semi-dilute and (ii) entanglement regime. The rheological response of the fluids was largely independent of bubble size but strongly dependent on ϕ. The viscous and elastic moduli increased with increasing bubble volume fraction, with elastic dominance prevalent at the higher gum concentration. Extensional rheometry, investigated using filament stretching, revealed that the thinning dynamics of the liquid thread were affected by bubble size, but the filament rupture time was primarily dependent on ϕ. The rheological behaviour in both shear and extension could be modelled as a single mode Giesekus fluid, with a single set of parameters able to describe both the shear and extensional behaviour in the semi-dilute regime. In the entanglement regime the single mode Giesekus fluid could fit the shear data or the extensional data individually, but not both. The fitted Giesekus fluid model parameters exhibited a strong dependency on ϕ, offering a way to predict the flow behaviour of these complex food fluids.

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 liquid foods are ubiquitous, from beverages to baked products, ice creams, dairy systems and confectionery, *e.g.* van Aken (2001). Aeration yields a softer texture, increased spreadability, a more homogeneous appearance and a more uniform distribution of taste (Thakur et al., 2003). 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; Gonnermann and Manga, 2007) and in other industrial sectors in the form of foamed cement (Ahmed et al., 2009), extracted crude oil (Abivin et al., 2009), cosmetics and personal care products (Malysa and Lunkenheimer, 2008).

It is important to understand the rheology of these aerated materials in order to develop and improve manufacturing routes. The presence of the bubble phase modifies the behaviour of the liquid, giving rise to shear-thinning and viscoelastic behaviour (Llewellin et al., 2002; Torres et al., 2013). 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 is usually discussed with reference to the capillary number, *Ca*, which compares the deforming stress arising from fluid shear to the restoring capillary pressure (Rust and Manga, 2002). However, other workers that have studied emulsions (*e.g.* Golemanov et al., 2008) have demonstrated that *Ca* is not a reliable indicator of the transition in densely populated systems as the shear stress acting on the dispersed phase in high volume fraction systems will differ noticeably from that in the continuous phase alone owing to bubble/droplet crowding effects. Llewellin et al. (2002) provided a good review of the pertinent literature as part of their work presenting a model for bubbly liquid rheology under steady and oscillatory shear conditions.

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Nomenclature

Roman

A	dimensionless group defined in Eq. (19), –
a	Giesekus mobility parameter, –
Bo	Bond number, –
Ca	Capillary number, –
c^*	critical concentration, g/L
D	filament diameter, μm
D_b	filament diameter at breakup, μm
D_{mid}	diameter of the filament at midpoint, μm
D_0	initial sample diameter, μm
D_1	diameter of the filament when first formed, μm
d_{max}	largest measured bubble diameter, m
d_{min}	smallest measured bubble diameter, m
d_n	Needle diameter, m
k	time constant, s^{1-n}
g	gravitational constant, m/s^2
G'	storage modulus, Pa
G''	loss modulus, Pa
M_n	number average molecular weight, g/mol
M_w	weight average molar mass, g/mol
M_z	higher average molecular weight, g/mol
n	flow index, –
n_b	number of bubbles, –
n_2	parameter in shear expression
N_c	number of classes of bubbles, –
p	probability, –
Q	volumetric flow of fluid within needle, m^3/s
R_{pp}	radius of parallel plate geometry, m
R^2	square of the correlation coefficient, –
t	time, ms
t_{cap}	capillary time, s
t_F	time to capillary break-up, ms
T	torque, N m
w	class interval width, m
X	filament shape factor, Eq. (9), –

Greek

α	surface tension between liquid phase and the air, N/m
δ	phase angle
ε	Hencky strain, –
$\dot{\varepsilon}$	Hencky strain rate, s^{-1}
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}
η_{app}	apparent viscosity, Pa s
η_e	estimated apparent extensional viscosity, Pa s
η_0	zero-shear-rate viscosity, Pa s
η_{r0}	relative viscosity at low shear rate, –
η_r	relative viscosity, –
η_∞	infinite shear rate viscosity, Pa s
Λ	group used within shear expression
λ	relaxation time, ms
μ	mean, μm
ρ	density, $kg\ m^{-3}$
ρ_s	density of aerated sample, $kg\ m^{-3}$
ρ_{us}	density of de-aerated sample, $kg\ m^{-3}$
σ	standard deviation

Most of studies on bubbly liquids in food and other applications have considered systems where the liquid phase is Newtonian (*e.g.* Thompson et al., 2001; Llewellin et al., 2002; Rust and Manga, 2002). Many bubbly liquids used in food manufacture feature non-Newtonian solutions or suspensions as the continuous phase. Examples include cake batters, and whipped creams and shortenings prepared by incorporating significant volumes of air into a viscous hydrocolloid matrix. Several natural water-soluble polymers, such as guar gum, are in widespread use in the food industry. The presence of a significant number of bubbles renders them strongly visco-elastic (Torres et al., 2013) and the existing theoretical treatments for bubbly liquids are not able to describe such materials. Similar findings were reported for cake batters (Meza et al., 2011; Chesterton et al., 2011a).

Food processing operations expose bubbly liquids to steady shear and extensional flow, and being able to predict behaviour in both modes is important for design and formulation of new food products. Experimental investigation of extensional flows is challenging, particularly for viscoelastic materials (Vadillo et al., 2012), partly due to difficulties in creating a purely extensional flow. Much of the work on extensional rheology has considered well characterised, model synthetic polymer solutions, and there is little published on the behaviour of systems containing guar gum and its derivatives, besides that by Tatham et al. (1995), Duxenneuner et al. (2008) and Bourbon et al. (2010) over a narrow range of concentrations (0.39–0.97 g/L) using a capillary breakup extensional rheometer (CaBER) device. Torres et al. (2014a) presented measurements of the extensional rheology of unaerated guar gum solutions obtained using the Cambridge Trimaster filament stretching device (Vadillo et al., 2010) over a wider range of concentrations (1–20 g/L), crossing the transition from the dilute to the entangled regime. To our knowledge, the effect of air volume fraction on the extensional properties of bubbly liquids prepared with guar gum or similar biopolymers has not been reported previously. This paper reports a systematic investigation of the effect of bubble volume fraction on the shear and extensional behaviour of aerated bubbly liquids with guar gum solutions as the continuous phase. Two guar gum concentrations are considered: one exhibiting semi-dilute behaviour, and another giving solutions in the entanglement regime.

Many mathematical treatments of extensional behaviour have been derived (Bird et al., 1987; Larson, 1988). Most testing has been conducted with shear flows, and the reliability of these equations for strongly extensional flows, where a substantial degree of stretching is anticipated, is not well understood (Gupta et al., 2000). In a companion paper (Torres et al., 2014b), we demonstrated that the Giesekus constitutive equation (Giesekus, 1982), which was originally developed to describe the shear behaviour of polymer solutions, can provide a good description of the shear and extensional rheology of unaerated aqueous guar gum solutions in the semi-dilute regime. That study suggested that simple shear tests could be used to give a reliable estimate of extensional behaviour for Giesekus fluids when a common set of parameters describe both types of flow.

The particular aim of this work is to extend the current framework for understanding the behaviour of bubbly liquids prepared with a non-Newtonian liquid phase to include their extensional rheology. The influence of ϕ on steady shear, oscillatory shear and extensional shear of bubbly liquids prepared with aqueous guar gum solutions was investigated experimentally. Bubble size distributions were modified by syringing. The single mode Giesekus fluid model, which describes the rheology of the unaerated solutions well, is shown to provide a reasonable description of these aerated systems with $\phi \leqslant 0.25$. The effect of ϕ on the Giesekus fluid parameters is presented, in analogy to studies of solids volume fraction on suspension behaviour.