Journal of Non-Newtonian Fluid Mechanics 215 (2015) 31–39

Contents lists available at ScienceDirect

Journal of Non-Newtonian Fluid Mechanics

journal homepage: http://www.elsevier.com/locate/jnnfm

Rheological behaviour of suspensions of bubbles in yield stress fluids

Lucie Ducloué [*], Olivier Pitois, Julie Goyon, Xavier Chateau, Guillaume Ovarlez

Laboratoire Navier (UMR CNRS 8205), Université Paris-Est, 77420 Champs-sur-Marne, France

ARTICLE INFO

Article history:
Received 23 May 2014
Accepted 15 October 2014
Available online 7 November 2014

Keywords:
Yield stress fluid
Bubble
Capillarity
Suspension
Emulsion

ABSTRACT

The rheological properties of suspensions of bubbles in yield stress fluids are investigated through experiments on model systems made of monodisperse bubbles dispersed in concentrated emulsions. Thanks to this highly tunable system, the bubble size and the rheological properties of the suspending yield stress fluid are varied over a wide range. We show that the macroscopic response under shear of the suspensions depends on the gas volume fraction and the bubble stiffness in the suspending fluid. This relative stiffness can be quantified through capillary numbers comparing the capillary pressure to stress scales associated with the rheological properties of the suspending fluid. We demonstrate that those capillary numbers govern the decrease of the elastic and loss moduli, the absence of variation of the yield stress and the increase of the consistency with the gas volume fraction, for the investigated range of capillary numbers. Micro-mechanical estimates are consistent with the experimental data and provide insight on the experimental results.

1. Introduction

Yield stress fluids are widely used in the industry where their versatile character, from solid under a critical stress to liquid above that threshold, has many applications [1]. Examples include creams and gels in the cosmetic industry, and also mud or fresh building materials like plaster or concrete slurries. During processing of those materials, air bubbles are often present in the fluid, either because they get entrapped during mixing or as the result of deliberate addition to confer innovative properties to the final product. This is for instance the case in dairy products [2] or in the building industry in which aerated materials are designed to be lighter and better insulating. Processing of these aerated yield stress fluids requires to understand and monitor their behaviour under shear flows.

Understanding the response of a sheared bubble suspension in a non-Newtonian fluid is complex: as the suspending fluid itself is non-Newtonian, the behaviour of the suspension is expected to be non-Newtonian too, and the contribution of additional non-linear phenomena due to the presence of the bubbles may be difficult to quantify. Some useful understanding of the physical mechanisms at stake can be collected from previous results on related cases of simpler suspensions. The simplest type of suspension is a dispersion of solid particles in a Newtonian fluid. The relative viscosity of such suspensions is an increasing function of the solid volume fraction which is well described by a Krieger–Dougherty law [3]. From a microscopic point of view, all the shear deformation undergone by the suspension occurs in the fluid between the solid grains. As a consequence, the effective local shear rate in the fluid has to be greater than the macroscopic shear rate applied to the suspension, leading to increased dissipation. Suspensions of bubbles in Newtonian fluids have been studied by Rust and Manga [4] and Llewellin et al. [5]: their experiments showed that the relative viscosity of the bubbly liquid in a steady shear flow increases with the gas volume fraction at low shear rate (with a lesser growth than the relative viscosity of particle suspensions) and decreases at high shear rate. Observation of the bubbles in the flow (also quantified in Rust and Manga [6]) evidenced the importance of bubble deformation in the contribution of the bubbles to the overall viscosity: bubbles in their experimental set-up are spherical at low shear rate and elongated in the flow at high shear rate. The distortion of flow lines around non-deformable bubbles leads to increased local shear rates in the suspending fluid compared to the macroscopic shear rate applied to the suspension. However, the absence of friction at the bubble surface lessens the total dissipation in the bubble suspension compared to the particle suspension. At high shear rate, the elongation of inviscid bubbles in the flow accommodates part of the shear deformation and decreases the total dissipation. This transition from stiff to soft bubbles with increasing shear rate is the result of a competition between two physical effects: the viscous stress in the fluid tends to stretch the bubbles in the flow whereas the capillary stress minimizes the bubbles' surface by favouring a spherical shape. To

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[*] Corresponding author.
E-mail address: lucie.ducloue@ifsttar.fr (L. Ducloué).

http://dx.doi.org/10.1016/j.jnnfm.2014.10.003
0377-0257/

Table 1
Synthetic description of all the concentrated emulsions used as model yield stress fluids to prepare bubble suspensions: nature and volume fraction of the oil dispersed phase, composition of the aqueous continuous phase (including the surfactant) and surface tension between the air and the continuous phase.

	Oil – vol. fraction	Continuous phase	σ (mN m^{-1})
Emulsion (1)	Dodecane – 73%	SDS 2.7% w. in water	36 ± 1
Emulsion (2a)	Silicon (V20) – 75%	Forafac® (DuPont™) 4% w. in water	15.5 ± 0.1
Emulsion (2b)	Silicon (V20) – 73%	Forafac® (DuPont™) 4% w. in water	15.5 ± 0.1
Emulsion (3)	Silicon (V350) – 79%	TTAB 3% w. in water/glycerol 50/50 w/w	35.5 ± 0.1
Emulsion (4a)	Silicon (V350) – 70%	TTAB 3% w. in water/glycerol 36/64 w/w	35 ± 1
Emulsion (4b)	Silicon (V350) – 70%	TTAB 3% w. in water/glycerol 36/64 w/w	35 ± 1

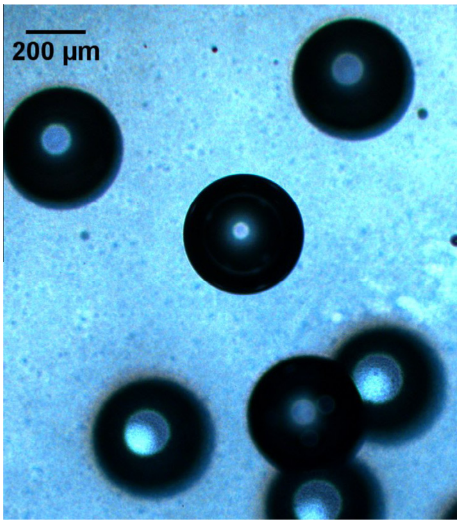

Fig. 1. Microphotograph of a bubble suspension in suspending emulsion 3. The bubble radius is 200 μm. The granulated background is emulsion 3, which is transparent.

quantify this competition, the authors introduce a capillary number that can be defined as "viscous" and is the ratio of the viscous stress to the capillary stress: $Ca_{visc} = \frac{\eta\dot{\gamma}}{\sigma/R}$ where η is the viscosity of the suspending fluid, $\dot{\gamma}$ is the applied shear rate, σ is the surface tension between the gas and the liquid and R is the bubble radius.

The case of suspensions in non-Newtonian fluids is more complicated as the local shear rate between the particles, and consequently the apparent viscosity of the interstitial fluid, is not known. Numerous experiments have been performed on filled polymer melts, which are dispersions of rigid particles in visco-elastic fluids and have large industrial applications [7]. The results obtained by Poslinski et al. [8] on suspensions of glass spheres in a polymer melt shed light on two important effects of particle addition in a non-Newtonian fluid. In the absence of fillers, the suspending fluid considered by the authors is Newtonian at low shear rate, and then shear-thinning for higher shear rates. When particles are added to the fluid, the viscosity of the suspension is increased for all shear rates, and the Newtonian plateau gets shorter and shorter as the solid volume fraction increases. The onset of shear-thinning in the suspension for lower shear rates is due to shear amplification in the fluid between the particles, in which the effective local shear rate can be high enough to get off the Newtonian plateau even though at the macroscopic shear rate applied to the suspension the fluid alone would still be Newtonian. The overall response of the suspension reflects the coupling of the fluid rheology to the flow lines perturbation caused by the inclusions. Suspensions of particles in yield stress fluids have been studied by Mahaut et al. [9] who characterized the elastic and plastic response of suspensions of hard spheres in a Herschel–Bulkley fluid. Below the yield stress, the elastic modulus of the suspensions grows with the solid volume fraction and follows a Krieger–Dougherty law, as can be expected from the viscosity of suspensions in Newtonian fluids: both measurements characterize the linear response of each suspension. The yield stress increases with the solid volume fraction too, and its growth, of smaller magnitude than the one of the linear properties of the suspensions, is well predicted by micro-mechanical estimates [10]. For shear thinning yield stress fluids, the lesser growth of the yield stress compared to the linear properties of the suspension can also be understood as a manifestation of shear amplification in the fluid between the grains. The local shear rate in the suspending fluid is higher than the macroscopic shear rate applied to the suspension and increases with the solid volume fraction, leading to decreasing apparent (secant) viscosity of the interstitial fluid. The overall response results from the interplay of flow lines perturbation and apparent fluidification of the suspending fluid.

Bubbly yield stress fluids have been the subject of fewer studies. Besides stability studies [11,12], their elastic properties have been studied in detail in Ducloué et al. [13] and a first description of the rheology of mixtures of foams and pastes has been given in Kogan et al. [14]. However, more work is needed to investigate a broader range of rheological parameters for the yield stress fluid and to describe the flow properties of those suspensions. We anticipate from the results on bubble suspensions in Newtonian fluids that the rheology of an aerated yield stress fluid will also be the result of the interplay of the suspending fluid rheology and capillary forces acting on the bubble surface. Yield stress fluids behave as visco-elastic solids below their yield stress and visco-plastic fluids above that threshold. We are thus interested in the visco-elastic properties, yield stress and flow curve of suspensions of bubbles in those fluids. In this aim, we perform an experimental study of the overall rheological properties of model suspensions of bubbles in tunable yield stress fluids. We limit to gas volume fractions up to 50% so that we do not consider foams of yield stress fluids, in which the bubbles are deformed by geometrical constraints.

In Section 2, we present the materials used for the study, and the rheometrical procedures. In Section 3, we discuss the complex shear modulus of a soft aerated solid. In Section 4, we review our results for the plasticity threshold of bubbly yield stress fluids. Section 5 is dedicated to the flow characterization of our suspensions.

2. Materials and methods

To perform this experimental study, we prepare model suspensions of monodisperse bubbles in simple yield stress fluids. For most systems, the suspensions are obtained by mixing a simple yield stress fluid with a separately produced monodisperse foam.

2.1. Model yield stress fluids

The simple yield stress fluids that we choose to perform the study are concentrated oil in water emulsions. By changing the chemical composition of the two phases and the oil volume fraction, we obtain various suspending emulsions with elastic moduli ranging from 100 to 1000 Pa and yield stresses between 10 and 40 Pa. Unless