Effect of polydispersity and bubble clustering on the steady shear viscosity of dilute bubble suspensions in Newtonian media

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Abstract

This work examines the steady shear viscosity of dilute polydisperse bubble suspensions generated in a mixture of mineral oil and span 80. We proved theoretically that, in polydisperse bubble suspensions, the shear-thinning behavior spans a capillary number (Ca) range between 0.01 and 100, instead of occurring at Ca~1, which is the case for monodisperse suspensions. However, for the effect of polydispersity to become apparent, the bubble size distribution should be bimodal, with very small and very large bubbles having similar volume fractions. In any other case, we can consider the polydisperse suspension as monodisperse, with a volume-weighted average diameter (d_{43}). To confirm the theoretical results, we carried out steady shear rheological tests. Our measurements revealed an unexpected double power-law decay of the relative viscosity. To investigate this behavior further, we visualized the produced bubble suspensions under shear. The visualization experiments revealed that bubbles started forming clusters and threads at average capillary number around 0.01, where we observed the first decay of viscosity. CFD simulations confirmed that under the presence of bubble clusters and threads the fluid streamlines distort less, thus resulting in a decrease of the suspension viscosity. Consequently, we can attribute the first decay of the relative viscosity to the formation of bubble clusters and threads, proving that the novel shear-thinning behavior we observed is due to a combination of bubble clustering and deformation.

Introduction

The presence of bubbles has been shown to change the viscosity of the ambient fluid, inducing shear-thinning and other viscoelastic phenomena, even in Newtonian ambient fluids (Llewellin et al., 2002a, 2002b; Mader et al., 2013). Several studies have focused on the rheology of monodisperse bubble suspensions, advancing constitutive equations to describe their steady shear viscosity (Llewellin et al., 2002a, 2002b). However, to our knowledge, the issue of polydispersity has been sparsely studied, with most of the published papers providing empirical constitutive equations that strongly depend on experimental data. In this work, we aim to clarify the role of polydispersity through a simple theoretical analysis, validated with steady shear rheological experiments.

To characterize the equilibrium configuration of bubbles under steady shear, the *Capillary number* is used:

$$\mathrm{Ca} \equiv \frac{\mu \alpha \dot{\gamma}}{\sigma} \qquad (1)$$

where μ is the viscosity of the ambient fluid, $\dot{\gamma}$ is the shear rate, α is the radius of a relaxed undeformed bubble and σ is the surface tension of the ambient fluid in air.

For $\mathrm{Ca} \ll 1$, the suspended bubbles are spherical and obstruct the flow, resulting in increased suspension viscosity. On the other hand, for $\mathrm{Ca} \gg 1$, the bubbles deform significantly and align with the fluid streamlines, causing a decrease in the suspension viscosity. Between these two extremes, the suspension shear-thins. For monodisperse suspensions, the onset of the shear-thinning behavior is at values of the capillary number of unit order of magnitude ($\mathrm{Ca} \sim 1$) (Llewellin et al., 2002a, 2002b; Mader et al., 2013).

To account for the effect of polydispersity, one can treat the dilute polydisperse suspension as the combination of N monodisperse components with a characteristic radius α_i and a bubble volume fraction φ_i. By calculating the relative viscosity for each size class and then summing the individual viscosity contributions, we obtain the relative viscosity of the polydisperse suspension (Mader et al., 2013). Following this method, we investigated the steady shear viscosity of dilute polydisperse bubble suspensions with bimodal and gamma size distributions. Our theoretical analysis proved that the effect of polydispersity becomes apparent only when the bubble size distribution is bimodal, with very small and very large bubbles having similar volume fractions. In any other case, we can model the polydisperse bubble suspension as monodisperse, with a volume-weighted average bubble diameter (d_{43}).

To confirm the theoretical results, we carried out steady shear rheological tests, which revealed a double power-law decay of the relative viscosity, a trend that cannot be supported by our theoretical analysis on polydispersity. To investigate this behavior, we visualized the produced bubble suspensions under shear.

Experimental Facility

To generate the bubble suspensions, we used a custom-made aeration device, offering simultaneous aeration and mixing (Fig. 1). The system consists of a propeller with attached aeration plates, covered with ceramic 2μm-porous filters. The ambient fluid for our suspensions was a mixture of mineral oil and 0.57 mol/L span 80 ($\mu = 4.2\ \mathrm{Pa \cdot s}$). To determine the bubble size distribution, we used optical microscopy, followed by image analysis. We measured the steady shear viscosity of the produced bubble suspensions using an Anton Paar MCR502 stress-controlled rotational rheometer.

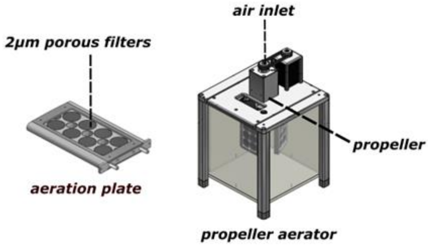

Figure 1: Aeration device used to produce the bubble suspensions.

To visualize the bubble suspensions under shear, we modified the setup of the rheometer with a glass bottom plate (Anton Paar Peltier Universal Optical Device - P-PTD 200/GL) to allow optical access, and we recorded the images during the steady shear tests using a Zyla 5.5 sCMOS camera, a Nikon mono zoom lens and a white led light as illumination.

Results and Discussion

Indicative experimental results for a bubble suspension with a total volume fraction $\varphi = 10.4\%$ are presented here. The tested sample was found to be polydisperse, with bubble radii following the gamma distribution between 10 and 170 μm, and d_{43} equal to 165 μm. The steady shear rheological measurements revealed a shear-thinning behavior with a double power law decay of the suspension relative viscosity (Fig. 2). The first decay happened at average capillary number ($< Ca >$) around 0.01, while the second started at $< Ca > \sim 1$. As discussed above, this first viscosity drop is not predicted by the theoretical analysis on polydispersity.

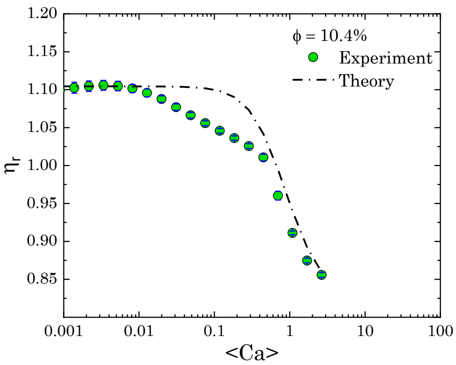

Figure 2: Experimental vs theoretical relative viscosity for a polydisperse bubble suspension with $\boldsymbol{\varphi = 10.4\%}$.

The visualization experiments revealed that at low $< Ca >$ of order 0.001, bubbles are uniformly dispersed. However, as the average capillary number increases, bubbles start aligning to form bubble threads, or getting closer to each other, creating clusters. The phenomenon becomes progressively more evident in the capillary number range 0.01 to 1, where we also notice the first decay of viscosity. We believe that the formation of bubble threads and clusters is responsible for the first decay of viscosity.

To validate this assumption, we performed computational fluid dynamics (CFD) simulations, considering a simple 2D steady shear flow of a Newtonian fluid around four solid spheres, and examined how different arrangements of the spheres affected the fluid streamlines. As seen in Fig. 3, for randomly positioned spheres, the fluid streamlines distort around each sphere. However, when the spheres are aligned or clustered, there is no flow in the interstitial spaces, and consequently the fluid streamlines distort less, leading to a decrease in the suspension viscosity.

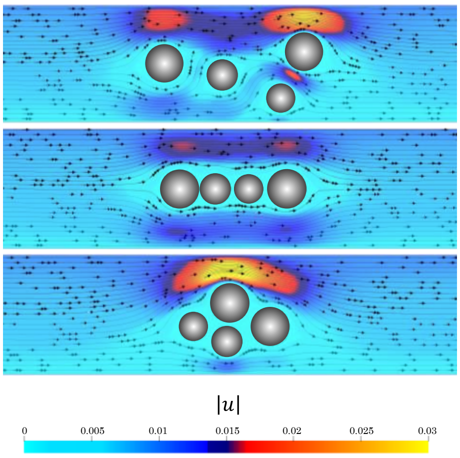

Figure 3: Velocity profiles of a 2D steady shear flow of a Newtonian fluid around solid spheres.

Conclusions

In this work, we described the complex shear-thinning behavior of dilute polydisperse bubble suspensions under steady shear, by explaining the effect of polydispersity and shear-induced clustering. The effect of polydispersity becomes important only if the total bubble volume fraction is divided equally between very small and very large bubbles. Under real experimental conditions, where often the bubble sizes follow the gamma distribution, we can regard the polydisperse suspension as monodisperse with a volume-weighted average diameter. Steady shear rheological experiments showed an unexpected double power-law decay of suspension relative viscosity. While the second decay can be attributed to bubble deformation, the first is caused by the formation of bubble clusters and threads, which facilitate the flow around them.

References

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