Rheological Simulation of In-Line Bubble Interactions

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The bubble behavior, especially their interactions, in non-Newtonian fluids is of key importance in such diverse fields as polymer devolatilization, composites processing, boiling, bubble column, fermentation, cavitation, plastic foam processing, and bubble absorption. Compared with the understanding of bubbles in Newtonian fluids, the study of the bubble behavior in non-Newtonian fluids remains still in an elementary stage, as pointed out by Ghosh and Ulbrecht (1989). Due to the inherent complex nature of bubble phenomena, a complete theoretical analysis is impossible at present. A somewhat simplified starting point in this field has been the study of bubbles formed from a single submerged orifice, which excludes mutual influence of bubbles formed in neighboring orifices. The first major work on the gas bubble motion in non-Newtonian fluids was performed by Astarita and Apuzzo (1965). Since then, there have been investigations. The results available in the literature provided essentially experimental information on the rise velocity of a single bubble vs. its volume in power-law non-Newtonian fluids. Until now, few publications were devoted to the study of bubble interactions and coalescence (Trambouze, 1993). Nevertheless, the loss of interfacial area due to coalescence can be a serious matter in gas-liquid contactors.

The final stage of coalescence is the rupture of the thin film of non-Newtonian fluid separating two bubbles, a matter that has received some attention (Acharya and Ulbrecht, 1978). However, an equally important problem, about which there is no information in the literature, is the manner in which bubbles draw together before film drainage and rupture processes. This is the topic for consideration in this note.

Experimental Studies

The experiments were carried out in a setup consisting of a Plexiglas cylindrical tank surrounded by a square duct. The diameter of the tank is 0.30 m and its height is 0.50 m. The square duct allowed to overcome optical distortions for visualization. The air bubble injection was realized by using six different orifices of varying diameters ($0.2\text{-}5 \times 10^{-3}$ m), submerged in the fluid on the center at the bottom section of the tank. A great reservoir was used to avoid any fluctuations due to bubble formation and detachment. An electronic valve of rapid response (≤ 8 ms) and a microprocessor permitted the injection of bubbles of determined volume with the desired injection period. The volume injected was proven very reproducible by means of the image analysis. The bubble rise velocity and the frequency of bubble formation were measured by two optical probes of photodiodes placed at two different heights. If there was no coalescence between two probes, the recorded pulses corresponding to the passage of bubbles were regular, and the formation frequency measured by two probes was also the same.

Results and Discussion

Three non-Newtonian fluids were used in this work: 1.7 wt. % of carboxymethylcellulose (CMC) in a mixture of 44.6–53.7 wt. % water-glycerol; 1 wt. % polyacrylamide (PAAm) in 99% water and 1.5 wt. % PAAm in a mixture of 49.25–49.25 wt. % water-glycerol. These fluids showed a shear-thinning viscosity which was evaluated in a rheometer RFS II (Rheometrics Inc., USA) and could be fitted perfectly by the Cross model. As normal stresses were too small to be measured accurately in these fluids, stress relaxation measurements after sudden cessation of steady shear flow were performed. At the same shear rate, the relaxation time for the CMC, 1% PAAm and 1.5% PAAm solutions was respectively of the order of 2, 9 and 12 s. Therefore, the 1.5% PAAm solution may be seen as the most elastic, while the CMC solution is the least one.

Typically, in-line interactions will accelerate the bubble rise velocity in Newtonian fluids (Omran and Foster, 1977). The evidence of this behavior in non-Newtonian fluids was clearly brought up in this work: the influence of the injection period on the rise velocity is shown in Figure 1 for a bubble volume V_B of 1.37×10^{-6} m^3. An injection period of order of 3, 7 and 12 s was necessary to prevent the interactions between bubbles, respectively for the CMC, 1% PAAm and 1.5% PAAm

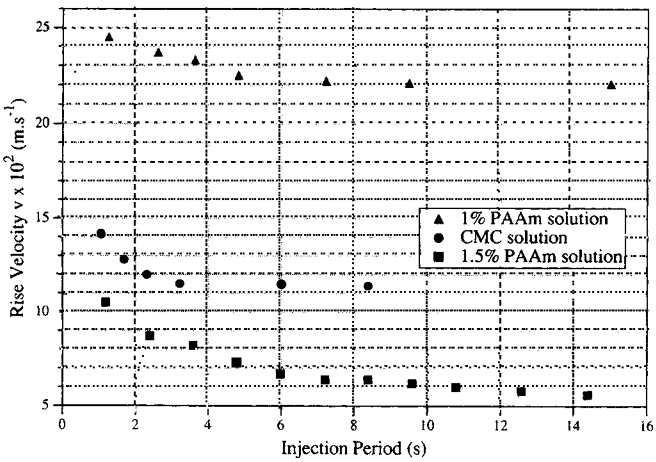

Figure 1. Influence of the injection period on the rise velocity.

Orifice diameter $d = 2\times 10^{-3}$ m; bubble volume $V_B = 1.37\times 10^{-6}$ m^3.

fluids. This corresponds approximately to the relaxation time. In the absence of interactions, the bubble rise velocity increased with the volume and seemed independent upon the orifice diameter. When the injection period became short enough (less than 1 s), the coalescence occurred.

In the literature, the interactions and coalescence of bubbles are a little better documented for Newtonian fluids, especially for water. In this case, the acceleration of the trailing bubble is usually considered as based on a decreasing drag within small distance, due to turbulence in the viscous wake induced by the leading one (De Nevers and Wu, 1971; Bhaga and Weber, 1980).

Respectively by means of a visualization method and a laser-Doppler anemometer, Coutanceau and Hajjam (1982) and Bisgaard (1983) have observed a peculiar phenomenon behind the leading bubble in a non-Newtonian fluid: the fluid went up with the bubble only in its vicinity; from a close distance behind the bubble, the fluid took an opposite direction and went down to form a "negative wake." The exact length of the negative wake is difficult to determine, because the negative velocity approaches zero very slowly. This effect is in general attributed to the elasticity of the fluid. In a pioneer work on anomalous wakes past solid spheres in viscoelastic fluids (Acharya et al., 1976), Acharya and Ulbrecht concluded that the inelastic fluids show a wide wake characteristic of the boundary layer separation for a flow past a sphere, whereas the viscoelastic fluids show the virtual elimination of the wake behind the sphere. This implies that the viscoelasticity causes a delayed separation. The major dissipation of energy occurs within the wake. Therefore, it is reasonable to assume that the viscoelastic fluids dissipate much less energy during the flow past a sphere than do the inelastic fluids. This could also offer at least a tentative explanation of the negative wake behind a bubble in such fluids.

Effectively, the wake behind a leading bubble can be considered responsible for the decreased drag in water. On the other hand, the negative wake in a non-Newtonian fluid isn't likely to explain the interactions and coalescence in non-Newtonian fluids. With respect to water, the high value of the viscosity of the non-Newtonian fluids used in this work will also easily absorb any turbulence created by the passage of a bubble. It may be noticed that compared with bubble rise in water, the Reynolds number is 300 to 6,000 times smaller in our fluids. Furthermore, another significant factor differentiating bubble-bubble interactions in non-Newtonian fluids from that in water is the long field of action. In the PAAm solutions, a following bubble can accelerate from a distance of 0.3 m behind the leading one and catch up with it. In a higher column, the interaction range could be hoped to cover greater distance.

A more plausible explanation may be the relaxation of stress induced by the passage of bubbles. The relaxation time of these stresses is determined by the fluid elasticity. However, a rigorous modeling of the interactions between bubbles is impossible as yet. So, we had the idea to simulate the passage of bubbles by imposing consecutive shear rates to a fluid sample by means of the rheometer RFS II which measured the response of the sample in term of shear stress. We call this original approach "rheological simulation." In the literature, the maximum shear rate corresponding to the rise of a bubble is defined as the ratio of the rise velocity to the equivalent diameter of the bubble: $\dot{\gamma}_{max} = v/d_{eq}$. For the passage of a chain of bubbles formed under a constant injection period T at a point in fluid for consideration, the simulated shear rate of each bubble was calculated by the following function

$$\dot{\gamma} = \frac{kv}{2h}\frac{1}{\cosh^2\xi} \quad \text{with} \quad \xi = \frac{v(t-T/2)}{h} \tag{1}$$

where $kv/2a = \dot{\gamma}_{max}$, h is a parameter related to bubble height, and k the magnitude of the shear deformation, v the bubble rise velocity, $\dot{\gamma}$ the shear rate, ξ a dimensionless parameter, and cosh the hyperbolic cosine function.

An example of the rheological simulation is shown in Figure 2: a history composed of four consecutive identical shear rates described by Eq. 1 was applied to a sample in the cone-and-plate geometry of the rheometer. Obviously, there was a gradual accumulation of stresses which had tendency to reach a stationary value. The magnitude of these unrelaxed or residual stresses could be considered as both strongly dependent upon the injection period and proportional to the

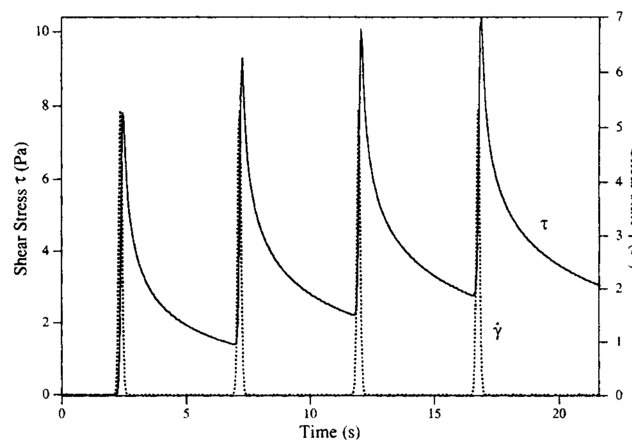

Figure 2. Accumulation of residual stresses after four consecutive identical shear rates in 1.5% PAAm solution.

Orifice diameter $d = 2\times 10^{-3}$ m; bubble volume $V_B = 1.37\times 10^{-6}$ m^3; injection period $T = 4.78$ s.

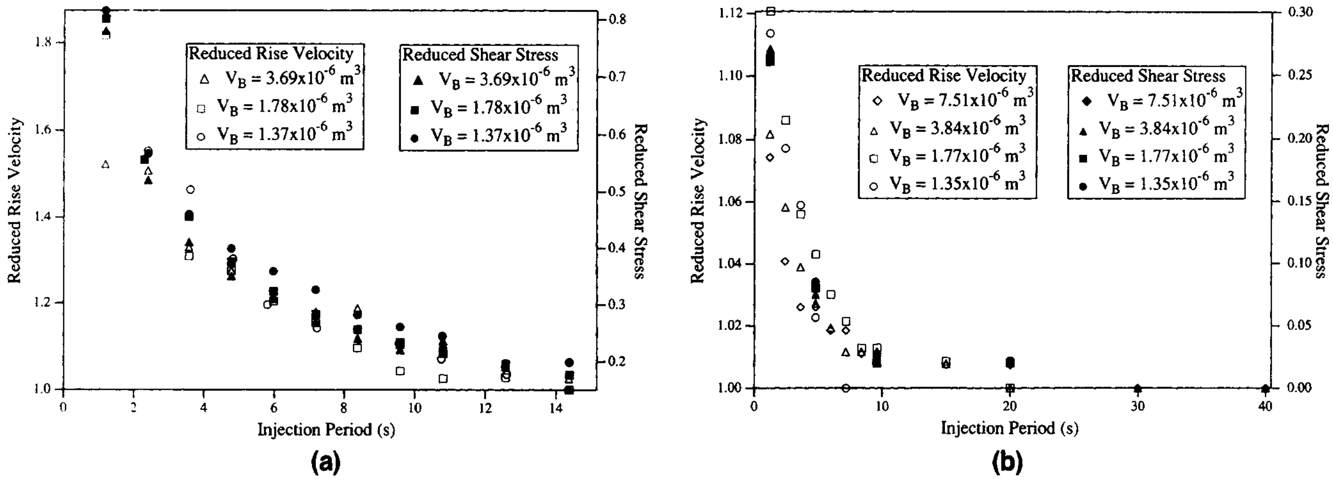

Figure 3. Agreement between the reduced rise velocity and reduced residual stresses in function of the injection period.

(a) 1.5% PAAm solution (orifice diameter $d = 2\times10^{-3}$ m); (b) 1% PAAm solution (orifice diameter $d = 1\times10^{-3}$ m).

elasticity of the fluid. In the light of these findings, the following scenario can be proposed: after the passage of a leading bubble, the memory effect of the elasticity holds the shear-thinning process during a certain time so that the local viscosity decreases, and the drag opposed to the trailing bubble is then reduced.

Similar rheological simulations were realized in these three fluids, taking especially into account the experimental values of rise velocity and injection period. Figure 3 shows a qualitative comparison between the reduced rise velocity and the reduced residual stress (normed respectively by the stationary rise velocity and the initial stress) as a function of the injection period. In spite of the scale difference between these two parameters, a close correlation does exist and provides evidence that the interactions should be essentially dominated by stress relaxation process. To our knowledge, such an approach isn't yet reported in the literature.

The reproducible and extensive experimental results show clearly that Figure 3 is not a coincidence or an artifact. From a conceptual point of view, the excellent agreement between the relaxation of residual stresses and the bubble interactions and coalescence in these non-Newtonian fluids can be explained by our current study in which the chaotic analysis is successfully applied to the coalescence between bubbles (Li et al., 1996). The positive largest Lyapunov exponent, the existence of a fractal dimension for the strange attractor, and broadened continuing spectral lines in the power spectrum qualify the investigated coalescence as chaotic. Particularly, the chaotic mechanism is deterministic with only 3 degrees of freedom (three control parameters). It is then possible to attribute the appearance of the chaos to a nonlinear dynamical competition between the creation and relaxation of shear stresses as shown by the rheological simulation presented in this note. The third control parameter is the bubble formation frequency at the orifice.

In the light of these results, the establishment of future models for interactions and coalescence will be hopefully possible in non-Newtonian fluids.

Conclusion

The original rheological simulation, taking into account the experimental injection period and bubble rise velocity, throws insight for the first time to the accumulation of residual stresses in non-Newtonian fluids after the passage of a chain of bubbles. The relaxation of these residual stresses, closely related to the drag decrease, is then the dominant mechanism governing the interactions and coalescence between bubbles.

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