Note on the Influence of Viscoelasticity on the Coalescence Rate of Bubbles and Drops

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In a series of earlier studies, we have reported on how the viscoelasticity of the ambient liquid influences the flow past a solid sphere (Acharya et al., 1976), a gas bubble (Acharya et al., 1977*a*), and a liquid drop (Acharya et al., 1977*b*). An associated phenomenon is the coalescence of bubbles and drops, the importance of which for the mass transport operations was recently reviewed by Narayanan et al. (1974). The role of the wake behind the leading drop/bubble in the coalescence process was recognized by Calderbank et al. (1965), and several mathematical models for these mechanisms were offered, for example, by De Nevers and Wu (1971) and by Crabtree and Bridgwater (1971). More recent models were critically reviewed by Narayanan et al. (1974) who also suggested a rational classification of the different types of wakes. The results of these papers lead to a conclusion that increased viscosity of the ambient liquid enhances the coalescence rate and results in reduced interfacial area. This phenomenon can be plausibly interpreted by assuming that the wake region behind the leading drop/bubble is much longer in a viscous liquid, so that the approaching particle is caught up in this wake at a much longer distance from the leading particle than it would be in a low viscosity liquid.

In many gas-liquid contactors used in the polymer and the fermentation industries, it is not only the viscosity (constant or shear dependent) but also the viscoelasticity which controls the overall liquid flow in general and the flow pattern around each particle in particular. With the needs of these two industries in mind, it would seem appropriate to examine the influence of viscoelasticity of the ambient liquid upon the rate of coalescence in some detail.

Coalescence is a complex process, and most of the wake models envisage it to take place in three stages:

1. In the first stage, the trailing bubble/drop enters the wake behind the leading particle.
2. Depending upon its size, the trailing particle experiences much less drag in the wake and thus approaches the leading particle rapidly until they collide and are then separated by a thin liquid film.
3. Provided that the outer forces press the two drops/bubbles together for a sufficiently long time, the ambient liquid is drained from the interparticle film until this bursts and coalescence occurs.

Following the arguments of Shiloh et al. (1973), the time needed for the two particles to collide (collision time) must be distinguished from the coalescence time, since the two steps are independent. It is quite common for two particles to collide with each other and then separate again.

In this short note we shall report some new observations regarding the influence of viscoelasticity upon the collision and coalescence times of drops and bubbles.

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EXPERIMENTAL

The experiments were carried out in a square (0.165 m × 0.165 m) perspex duct, the length of which was 2.450 m. For the observation of gas bubbles, the speed of the 35 mm Hycam high-speed cine camera was in the range of 150 to 200 p.p.s., while that for drops was 60 to 80 p.p.s. The films were analyzed using the PDP x-y analyzer, and the four following parameters were determined for each run: initial separation distance x_o, basal diameter d, collision time t_1, and coalescence time t_2. The initial separation distance and the basal diameter were varied by using different nozzles and burrettes discharging the bubbles/drops at different distances. In all experiments, air was used for bubbles, and nitrobenzene (dyed red with waxoline) was used to form drops. Aqueous solutions of carboxymethylcellulose and polyacrylamid (both at 0.5% concentration) were used as ambient liquids. The rheological parameters of both the polymer solutions were determined using a Weissenberg rheogoniometer type R18, where the liquid sample is sheared between a plate and a cone with large apex angle.

RESULTS AND THEIR DISCUSSION

Both the polymer solutions showed a shear dependent viscosity η which was evaluated from the measured torque T and the shear rate $\dot{\gamma} = \omega/\alpha$ (ω being the angular velocity and α the complementary apex angle) using the formula

$$\eta = 3T/2\pi R^3\dot{\gamma} \tag{1}$$

From the axial thrust F between the plate and the cone, the primary normal stress coefficient σ_1 was evaluated using the formula

$$\sigma_1 = 2F/\pi R^2\dot{\gamma}^2 \tag{2}$$

This coefficient represents a measure of the liquid's elasticity under steady state shear. Both η and σ_1 were found to depend upon the shear rate, and the data were satisfactorily interpreted by empirical functions

$$\eta = K\dot{\gamma}^{n-1} \quad \text{and} \quad \sigma_1 = A\dot{\gamma}^{b-2} \tag{3}$$

in the range of $0.1\ s^{-1} < \dot{\gamma} < 10^3\ s^{-1}$. The values of the coefficients K and A and of the exponents n and b are given in Table 1.

At low enough shear rates (of about 10 s^{-1}), both the polymer solutions have the same apparent viscosity of about 0.15 Nsm^{-2}. It may be assumed, therefore, that the influence of viscosity on both the collision and coalescence time was eliminated. At the same shear rate, the primary normal stress difference $\sigma_1\dot{\gamma}^2$ of the PAA solutions will be of the order of 0.14 N m^{-2}, while the CMC solution does not display any measurable normal stress difference. Therefore, the PAA solution may be seen as viscoelastic, while the CMC solution is, in this context, inelastic.

In order to assess the influence of elasticity on the

TABLE 1. PHYSICAL AND RHEOLOGICAL PROPERTIES OF THE FLUIDS USED

Solution	Density at 20°C kg m^{-3}	K N s^n m^{-2}	n	A N s^b m^{-2}	b	Shear rate (s^{-1}) at which parameters measured
0.5% CMC	$1.02 \cdot 10^3$	0.2	0.86	—	—	$1.0\text{-}10^3$
0.5% PAA	$1.008 \cdot 10^3$	0.78	0.3	2.65	0.713	$0.1\text{-}10^3$

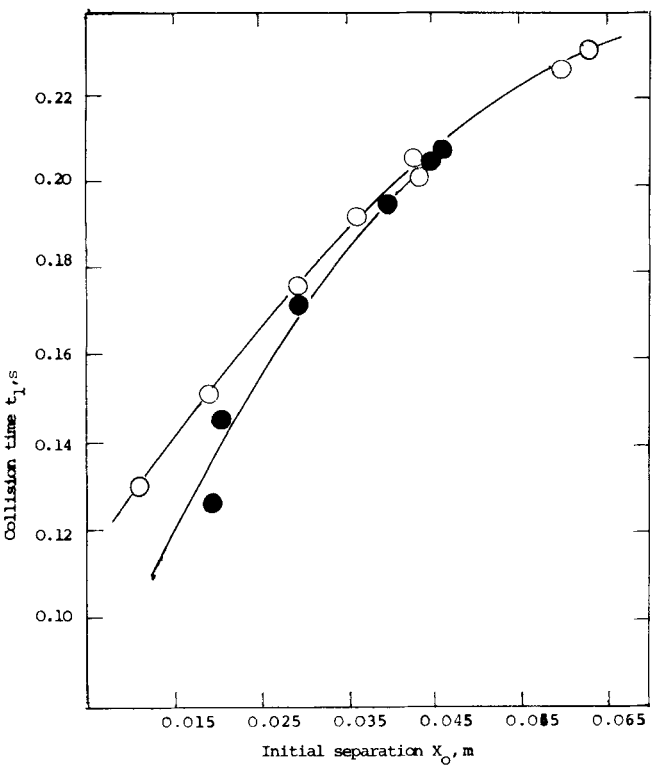

Fig. 1. Collision times of bubbles in inelastic CMC (●) and viscoelastic PAA (○) solutions plotted vs. the initial separation distance x_o.

collision time of air bubbles and liquid drops, the time t_1 was plotted vs. the initial separation distance x_o. The plots are shown in Figures 1 and 2 for bubbles and drops, respectively. Only data points obtained with particles having approximately the same diameter (about $1 \cdot 9.10^{-2}$ bubbles and 6.10^{-3}m drops) were used for this comparison so that the influence of the basal diameters is eliminated. In both cases, the elasticity of the continuous phase leads to an increase of the collision time, although both curves have essentially the same shape. Qualitatively, it can be said that the elasticity reduces the size of the toroidal wake behind a moving spherical particle, thus making the approach of the trailing particle slower.

The convergence of the two curves in Figure 1 is due to the fact that bubbles of around 2 cm diameter when traveling over long distances (after a large initial separation) are no longer spherical but assume a shape known as a spherical cap. The wake behind these caps is far more controlled by the interplay of inertia and viscosity, and the elasticity plays only a minor part.

We shall attempt to interpret this phenomenon against the background of the model suggested by Batchelor (1967). A far wake solution for the wake velocity obtained by Batchelor is given by

$$w = \frac{V\rho g}{4\pi\eta X} \exp\left[-\frac{Ur^2\rho}{4\eta X} \right] \tag{4}$$

In order to appreciate the accelerations involved in the process of bubble movements, dw/dX can be calculated, and we can assume that its magnitude is reasonably representative of the order of magnitude of the corresponding deformations in elastic fluids. We have

$$\frac{dw}{dX} = -\frac{V\rho g}{4\pi\eta X^2} \exp\left[-\frac{Ur^2\rho}{4\eta X} \right] + \left(\frac{V\rho g}{4\pi\eta X} \right)\left(\frac{Ur^2\rho}{4\eta X^2} \right) \exp\left[-\frac{Ur^2\rho}{4\eta X} \right] \tag{5}$$

For large X for which the solution is supposed to be valid, one gets

$$\frac{dw}{dX} = \frac{\overline{A}}{X^2}\left[\frac{\overline{B}}{X} - 1 \right] \tag{6}$$

where

$$\overline{A} = \frac{V\rho g}{4\pi\eta}$$

and

$$\overline{B} = \frac{Ur^2\rho}{4\eta}$$

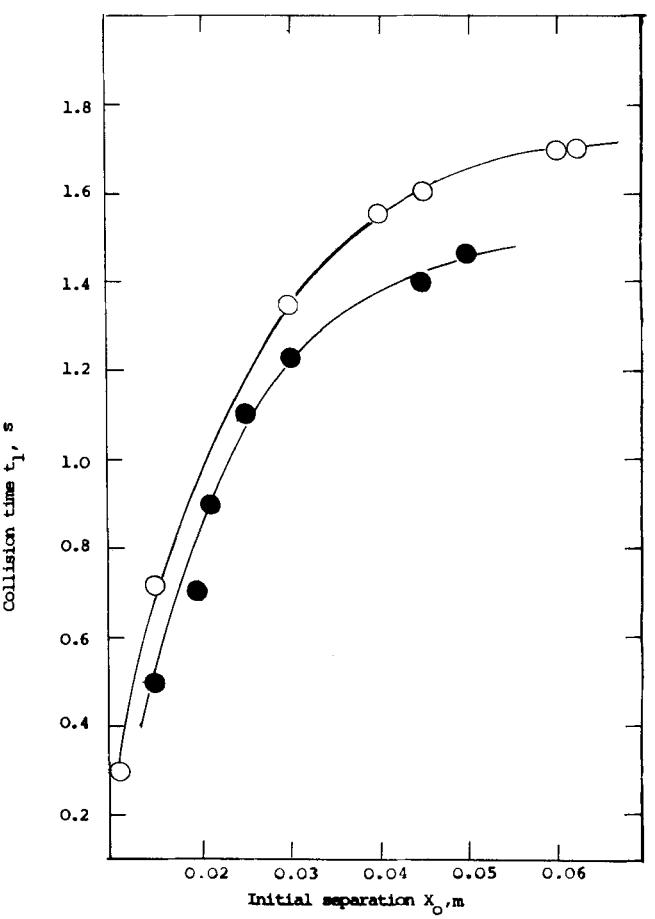

Fig. 2. Collision times of liquid drops in inelastic CMC (●) and viscoelastic PAA (○) solutions plotted vs. the initial separation distance x_o.

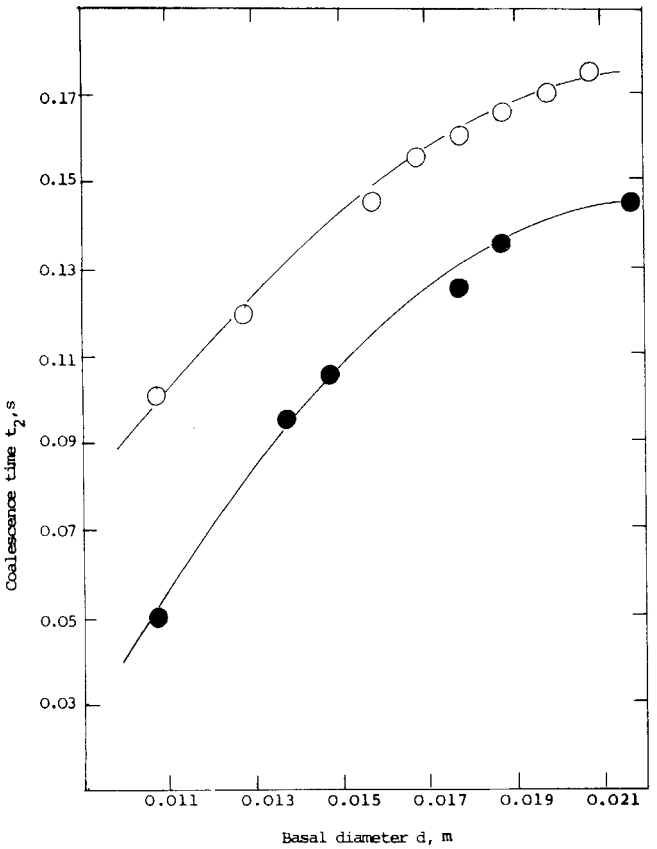

Fig. 3. Coalescence times of bubbles in inelastic CMC (●) and viscoelastic PAA (○) solutions plotted vs. the basal bubble diameter *d*.

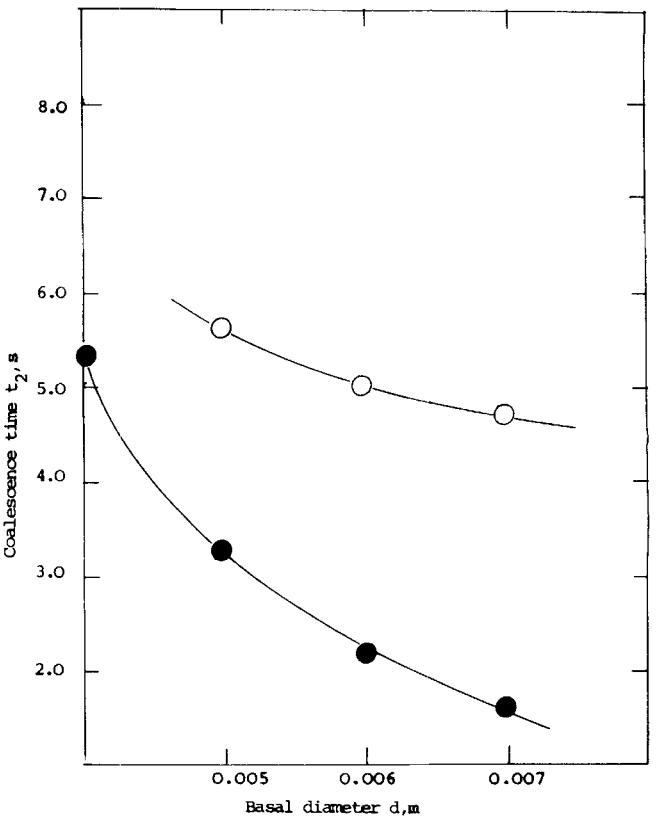

Fig. 4. Coalescence times of liquid drops in inelastic CMC (●) and viscoelastic PAA (○) solutions plotted vs. the basal drop diameter *d*.

The radial separation r of two spherical particles which are moving in a straight line is zero; thus

$$\frac{dw}{dX} = -\frac{\overline{A}}{X^2} \tag{7}$$

As a typical calculation, take $\rho = 1\,000$ kg m^{-3}, $g = 9.81$ ms^{-2}, and $\eta = 0.15$ Nsm^{-2}.

Consider a spherical particle which is about 0.02 m in diameter, separated from the leading bubble by $X = 0.03$ m. Then we have

$$\left| \frac{dw}{dX} \right| \simeq 200\ \text{s}^{-1} \tag{8}$$

It is immediately evident that the local accelerations in the wake are quite high compared with the typical characteristic liquid time λ which, for the purpose of this exercise, can be estimated using the relationship

$$\lambda = \frac{\sigma_1}{\eta} = \frac{A}{K}\dot{\gamma}^{b-n-1} \tag{9}$$

It turns out that the characteristic liquid time λ will be around 0.15 s; that is, its reciprocal value is thirty times smaller than the shear rate.

Typically, in cases when the deformation rates are too high for the liquid to respond, the kinematics of the flow will adjust itself to reduce the acceleration. The evidence of this behavior was clearly brought up by Metzner (1968). The consequence of a reduced acceleration is obviously a slower approach of the rear particle towards the leading one, that is, increased collision times, and, indeed, this has been observed experimentally.

After the two drops/bubbles collided, they could separate again if the draining of the liquid from the film which separates them is too slow or if the forces which tend to separate the particles are too strong.

From the work of van der Temple (1958) and Mackay and Mason (1963), we know that the film bursts when its thickness reaches about 300Å. The data shown in Figures 3 and 4 show that the coalescence times of both drops and bubbles are longer in viscoelastic PAA solutions than in inelastic CMC solutions; that is, the elasticity delays the coalescence process. All the data presented in Figure 3 have been obtained for equal initial separations of bubbles of about 0.05 m. The same applies to Figure 4.

In attempting to interpret the delayed coalescence in viscoelastic liquids, much can be learned from the so called squeeze-film experiments carried out by Brindley et al. (1976). They have shown that the half times for squeezing films of viscoelastic liquids were twice or three times higher than those of inelastic liquids. Seeing this from a purely mechanistic point of view, we can say that the viscoelastic fluid has a resistance towards being stretched which an inelastic fluid does not have. If the same behavior applies to coalescence of two bubbles or drops, then it is not surprising that the drainage of a viscoelastic liquid from the separating film takes much more time.

Thus, the elasticity and the viscosity counteract as they do in the case of diffusion induced bubble collapse (Zana and Leal, 1975).

It will be further noted that the coalescence times of drops and bubbles show an opposite trend when plotted vs. the basal diameter and that this applies both to the inelastic as well as viscoelastic fluids. Clearly,

this phenomenon has nothing to do with the rheological complexities of the ambient liquids, and its interpretation must be sought in the different behavior of bubbles and drops in liquids. The larger the bubble is, the larger the contact area between the concave face of the leading and the convex face of the trailing bubble cap. Thus, the area of the film to be drained increases with the increasing basal diameter of the bubble. On the other hand, drops in the region of diameters between 0.004 and 0.007 m remain essentially spherical.

CONCLUSIONS

The elasticity of polymer solutions has a tendency to increase both the collision and the coalescence times of gas bubbles and liquid drops. Thus, polymer additives with strong elastic component may reduce the overall coalescence rate considerably.

NOTATION

A = material parameter, Equation (3)
b = material parameter, Equation (3)
d = basal diameter of a bubble/drop
F = axial thrust between the cone and the plate of the R18 rheogoniometer
g = acceleration due to gravity
K = material parameter, Equation (3)
n = material parameter, Equation (3)
R = radius of the cone and plate setup
r = radial distance
t_1 = collision time
t_2 = coalescence time
T = torque between the cone and the plate of the R18 rheogoniometer
U = bubble rise velocity
V = bubble volume
w = wake velocity
X_o = initial separation of bubbles/drops
X = axial distance

Greek Letters

α = complementary apex angle between the cone and the plate in the R18 rheogoniometer
$\dot{\gamma}$ = shear rate
ω = angular velocity
η = apparent viscosity
ρ = density
λ = characteristic time of a viscoelastic liquid
σ_1 = primary normal stress difference

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An Electroconductivity Technique for the Measurement of Axial Variation of Holdups in Three-Phase Fluidized Beds

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A three-phase fluidized bed consists of solid phase particles fluidized by a gas and liquid flow. Although many schemes for contacting the three phases are possible, a common method is to fluidize the solid phase by the upward concurrent flow of gas and liquid. The liquid forms the continuous phase, while the gas and solids are dis-

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