Modifications in Bubbly Flow on Antifoam Addition

STANLEY Y. HOBBS
and
CHARLES F. PRATT

Synthesis and Characterization Branch
General Electric Corporate Research and Development
Schenectady, New York 12301

In a recent series of investigations we have used fritted glass bubbling tubes to evaluate various defoaming agents in aqueous systems. We have found that these antifoams can radically modify the flow regime in the bubbling liquid even when no additional surfactants are present. These observations are important in elucidating the mechanism of antifoam action as well as in extending data collected on small frit tubes to larger scale sieve trays.

The bubbling tube used in our experiments is diagramed in Figure 1. At low gas velocities and moderate liquid loadings, bubbly flow predominates with discrete spherical bubbles rising through the liquid. As the gas velocity is increased, the bubbles become somewhat larger and less spherical in shape as the result of differential shear across the bubble surface arising from increased turbulence in the liquid. At still higher gas velocities increased bubble agglomeration and eddying accompany fully developed churn-turbulent flow.

When wall effects are neglected and concentration and velocity profiles are uniform, the drift flux or superficial gas velocity can be empirically related to the void fraction of the froth in both the bubbly and churn-turbulent regions, as discussed by Wallis (1969). For the present discussion it is assumed that the drift flux in the bubbly flow region is described by

$$J_g = \mu_\infty \alpha (1 - \alpha)^{1/2}$$

where

$$\mu_\infty = 1.4\,(1 - \alpha)^{3/2} \left(\frac{\gamma g}{\rho}\right)^{1/4} \tag{1}$$

In the churn-turbulent region the drift flux is approximated as

$$J_g = \mu_\infty \left(\frac{\alpha}{1 - \alpha}\right) \quad \text{where} \quad \mu_\infty = 1.4 \left(\frac{\gamma g}{\rho}\right)^{1/4} \tag{2}$$

The empirical relationships are plotted as functions of void fraction in Figure 2.

EXPERIMENT

In a first experiment nitrogen was bubbled through 300 ml (25.5 cm liquid head) of quartz distilled water at superficial velocities ranging from 0 to 30 cm/s. The tube was carefully cleaned with Chromerge®, hydrofluoric acid, and distilled water prior to use. Froth heights were reproducible to ±2% over the entire gas flow range and no hysteresis was observed on increasing or decreasing the gas velocity. The data appear in Figure 2. The initial departure from the region of ideal bubbly flow began at approximately 3 cm/s although the void fraction continued to increase rapidly up to a gas velocity of 10 cm/s. At higher flow rates the void fraction dropped to a minimum of 0.58 as greater turbulence increased agglomeration. On the addition of 10 ppm GE AF-72 silicone antifoam, the departure from ideal bubbly flow occurred at roughly the same gas velocity as previously, but the void fraction increased much more slowly with the drift flux and did not rise beyond 0.51 until the gas velocity was greater than 20 cm/s. No change was observed when the antifoam level was reduced to 2 ppm or increased to 20 ppm.

The trend of these experiments follows very closely the results of Zuber and Hench (1962) who found that on perforated plates a maximum appeared in the void fraction-gas velocity curves with increased orifice number and decreased orifice size. Wallis (1961) noted a similar effect with decreasing water purity although further details on the nature or concentration of such impurities is not available. The changes in flow regime were attributed to changes in bubble agglomeration without further explanation.

Short pulse flash photography provides more detailed insight into these effects. Figure 3 is a photograph of the entrance region just above the glass frit at a gas velocity of 10 cm/s. The smallest bubble diameters are approximately 1 mm and disengagement from the frit is usually complete before appreciable bubble agglomeration has occurred. The bubbles remain spherical for approximately 1 cm above the plate before substantial distortion is seen. Relatively little agglomeration occurs in this region although some coalescence seems to be centered just above the primary entrance region. Many bubbles were observed to undergo multiple collisions without agglomeration. These observations were confirmed in a second experiment in which two air jets were opposed to each other in such a way that the bubbles collided after separation from the orifices. High speed motion pictures showed the impinging bubbles underwent compression and then rebounded elastically before the intervening film could drain to the point of rupture. Even when the two bubble streams were allowed to impinge prior to disengagement from the orifices, only a moderate amount of coalescence occurred.

A photograph of the entrance region above the glass frit after

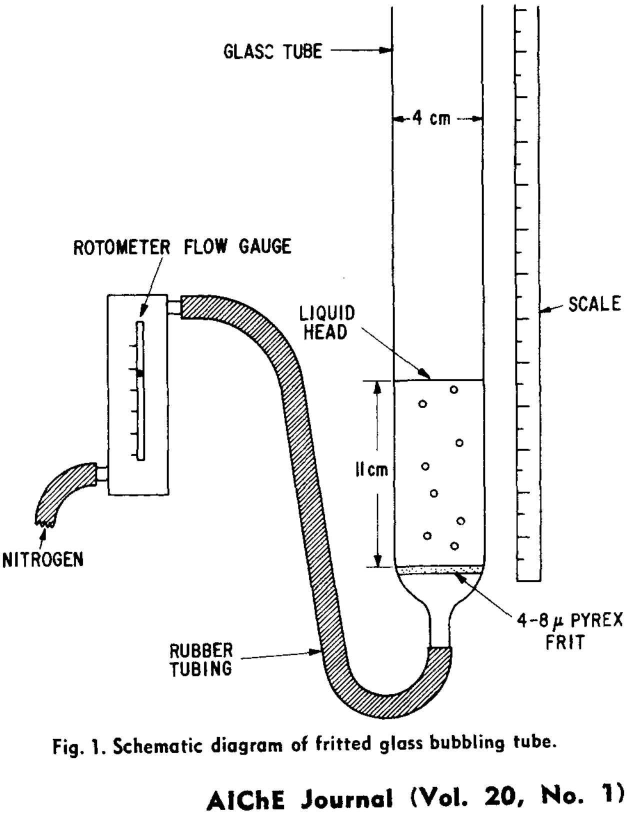

Fig. 1. Schematic diagram of fritted glass bubbling tube.

the addition of 10 ppm GE AF-72 antifoam to the distilled water appears in Figure 4. The liquid head and gas flow rate are unchanged although as indicated in Figure 2 the void fraction of the froth has been substantially reduced. Note the absence of small spherical bubbles above the frit with coalescence occurring primarily during formation of the bubbles before disengagement from the frit. Some further agglomeration was observed to result from bubble collision further up the liquid column. Repetition of the two-orifice experiment showed that as long as impingement took place after the bubbles were detached from the orifices, the collisions were primarily elastic. As the nozzles were placed closer together, however, agglomeration proceeded at a much faster rate than was observed in the absence of antifoam.

In a final experiment the frit was made hydrophobic by baking on a polydimethyl siloxane fluid at 300°C. Excess, nonbonded fluid was subsequently removed by thorough cleaning with benzene, acetone, and distilled water. The void fraction-velocity profiles for distilled water and distilled water plus 10 ppm AF-72 are presented in Figure 2. At low to intermediate superficial gas velocities the void fraction is substantially reduced by the presence of a hydrophobic frit. From 5 to 15 cm/s the void fraction is below that observed for distilled water with or without antifoam when a hydrophilic frit is used. As a result of the increased contact angle of water against polydimethyl siloxane the average bubble size increases by several diameters when a hydrophobic frit is used. It is primarily this effect and not increased agglomeration which displaces the data for distilled water toward the churn-turbulent flow region. This behavior is exactly analogous to the observation (Zuber and Hench, 1962) that increased hole size and separation bias bubble column data toward the region of churn-turbulent flow. Addition of 10 ppm AF-72 to the water causes further reduction in the void fraction for a given flow velocity. As in the case of the hydrophilic frit, this change in flow character results from increased coalescence of bubbles during formation on the frit.

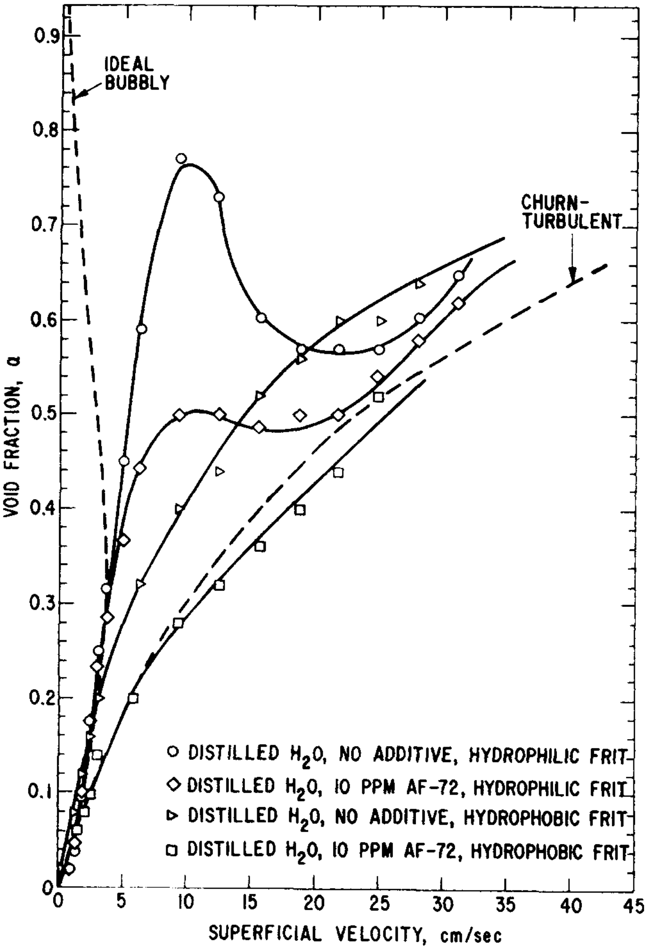

Fig. 2. Void fraction vs. superficial velocity data for distilled water and distilled water plus antifoam on hydrophobic and hydrophilic glass bubbling frits.

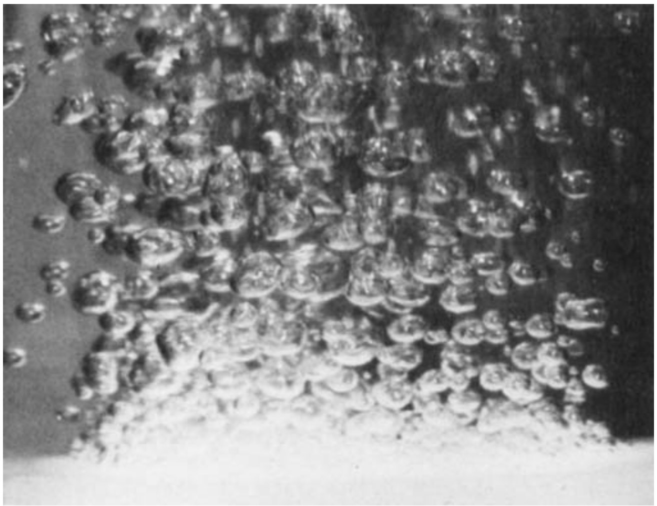

Fig. 3. Entrance region above hydrophilic glass frit using quartz distilled water. Note small, spherical bubbles and general absence of agglomeration.

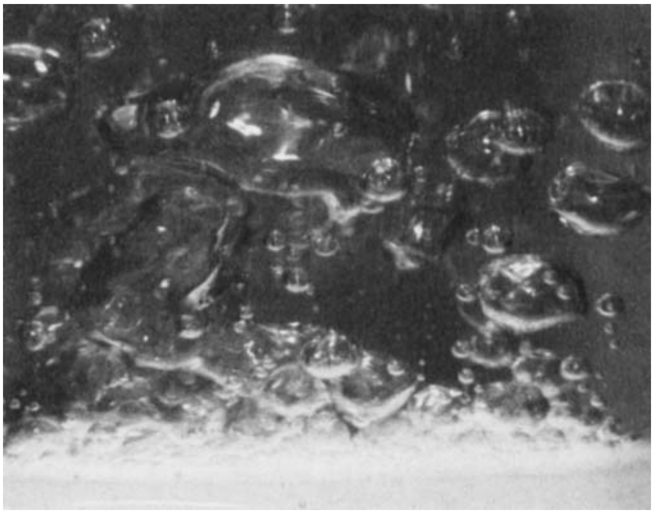

Fig. 4. Entrance region above hydrophilic glass frit using quartz distilled water plus 10 ppm AF-72. Note high incidence of bubble agglomeration on the frit.

CONCLUSIONS

1. The addition of an antifoaming agent to distilled water causes a major reduction in the froth void fraction at a given gas velocity. To a large extent this reduction results from agglomeration of neighboring bubbles prior to disengagement from the frit. Coalescence during passage up through the liquid plays a secondary role. The first effect is most pronounced at superficial velocities between 5 and 25 cm/s. At lower velocities the newly formed bubbles are too widely separated for agglomeration to occur prior to disengagement while at higher velocities the flow is so turbulent that the bubbly flow pattern breaks down in all cases.

2. The effect of antifoams is most noticeable when bubbles come into contact during formation. Under these

conditions the antifoam promotes localized thinning and rupture of the bubble walls which cause coalescence to precede disengagement from the frit. Once formed, however, air bubbles rising through the antifoam-containing liquid show a high degree of resistance to agglomeration even after repeated collisions.

In general, antifoams are employed to break up stable surface foams and it is suggested that they function by rapidly spreading on the bubble surface, sweeping away surfactant, and thereby rupturing the bubble. They appear to be most effective against thin-walled, well-drained foams. Our experiments suggest that similar conditions exist on the frit surface where substantial drainage can occur between bubbles while they are still held in contact by attachment to the frit. In contrast, in the bulk liquid colliding bubbles can separate from each other faster than interfacial drainage can occur and the relatively thick liquid film maintains bubble integrity even when antifoam is present.

3. Hydrophobic frits modify the flow regime primarily by increasing the average bubble size prior to disengagement and not by promoting agglomeration during bubble formation. In this respect they behave much more like perforated plates than their hydrophilic counterparts and may be more appropriate to use in modeling studies.

ACKNOWLEDGMENT

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NOTATION

α = void fraction

γ = surface tension

ρ = liquid density

g = gravitational constant

J_g = drift flux

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Creeping Flow of a Power-Law Fluid over a Newtonian Fluid Sphere

V. MOHAN

Department of Chemical Engineering
Indian Institute of Technology, Madras-600036, India

In a paper in this journal, Nakano and Tien (1968) investigated the creeping flow of a power-law fluid over a Newtonian fluid sphere and presented an upper bound on the drag. A combination of Galerkin's method and variational principle due to Johnson (1960) was used in their analysis. However, the functional they minimized is proportional to the energy dissipation rate for the external fluid alone and does not draw any contribution from the inside fluid. It is to be expected that the minimizing of the functional obtained by viewing the system as a whole will lead to the true upper bound on the drag. Following this approach it is shown in this work that the upper bounds are, in fact, below those of Nakano and Tien for values of the relative viscosity factors around 1. Such flow situations arise in liquid-liquid extraction, phase separation, and allied processes (Treybal, 1963).

Adopting the notations of Slattery (1972), the equations of continuity and motion are

$$\frac{\partial \rho}{\partial t} = -(\rho\, v^j)_{,j} \tag{1}$$

$$\rho\left(\frac{\partial v^i}{\partial t} + v^j\, v^i_{\ ,j}\right) = -p^{,i} + \tau^{ij}_{\ ,j} + \rho\, f^i \tag{2}$$

We make the same assumptions of flow as made by Nakano and Tien. The constitutive equations governing the flow are taken to be

$$\tau_l^{\ k} = 2\eta_i\, d_l^{\ k} \quad \text{(internal fluid)} \tag{3}$$

$$\tau_l^{\ k} = 2K\,(2\, d_j^{\ i} d_i^{\ j})^{(n-1)/2}\, d_l^{\ k} \quad \text{(external fluid)} \tag{4}$$

The equation of motion for the inside fluid reduces to

$$D^4 \psi_i = 0 \tag{5}$$

Let us define a function E as

$$E = \int_0^{\gamma^2} \eta(\gamma^2)\, d(\gamma^2) \tag{6}$$

where $\gamma^2 = d_i^{\ j}\, d_j^{\ i}$. It has been shown (Slattery, 1972) that for a homogenous function E,

$$tr\,(\tau \cdot D) = q\, E \tag{7}$$

$$\text{where}\quad \begin{aligned} q &= n + 1 && \text{for power-law fluids} \\ &= 2 && \text{for Newtonian fluids} \end{aligned}$$

We now seek to obtain the upper bound to the energy