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A note on single bubble motion in surfactant solutions

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This note addresses measurement of single bubble velocity in surfactant solutions and the physical model of the effect of surfactant concentration on the steady-state velocity. Continuous tracking of the bubble along the rise path is used as the measurement method. Using this technique, the steady-state velocity is found to be independent of surfactant concentration over a wide range, which contradicts the data frequently used to develop models.

Fdhila & Duineveld (1996) studied the effect of surfactant on the rise of single spherical bubbles of different sizes (radius from 0.4 to 1.0 mm). They measured the bubble velocity at 3.5 cm from the point of generation and observed a dependence on the bulk concentration of surfactant. The dependence was modelled using a stagnant cap model for bubble surface retardation with a cap angle as a function of surfactant concentration. These experimental data have also been used by others as a basis for theoretical or numerical models (McLaughlin 1996; Cuenot, Magnaudet & Spennato 1997; Dukhin, Miller & Loglio 1998; Wang, Papageorgiou & Maldarelli 1999).

Fdhila & Duineveld argued that the steady-state velocity is reached at 3.5 cm from the release point but no proof was offered. We find that the bubble velocity can depend strongly on the distance (time) travelled after release, particularly in dilute solutions.

A bubble rising in a surfactant solution accumulates surfactant molecules on its surface. The motion of the bubble pushes the adsorbed surfactant molecules from the front of the bubble to the rear, inducing a layer of non-uniformly distributed surfactant. This non-uniformity induces a surface tension gradient toward the front of the bubble which generates a tangential shear stress that retards the surface velocity and increases the drag coefficient. This phenomenon is called the Marangoni effect (Frumkin & Levich 1947; Levich 1962). Until steady state is reached, the drag coefficient continues to increase causing the bubble to decelerate.

The experimental set-up used here to detect the deceleration is shown in figure 1 (Sam, Gomez & Finch 1996). The column is 4 m high with a square cross-section of $10 \times 10\,\mathrm{cm}^2$. Bubbles are produced by introducing air through a glass capillary with a known inner diameter. Bubble generation is controlled by adjusting air pressure at a frequency where the motion of a bubble is not affected by the preceding bubble (less than about 1 bubble s^{-1}, Sam *et al.* 1996). The column has a jacket for circulating water to control the temperature (6–50 °C). A fibreglass measuring tape is installed inside the column to determine the position of the bubble. Using this set-up, the velocity–distance profile was tracked by the mobile video camera.

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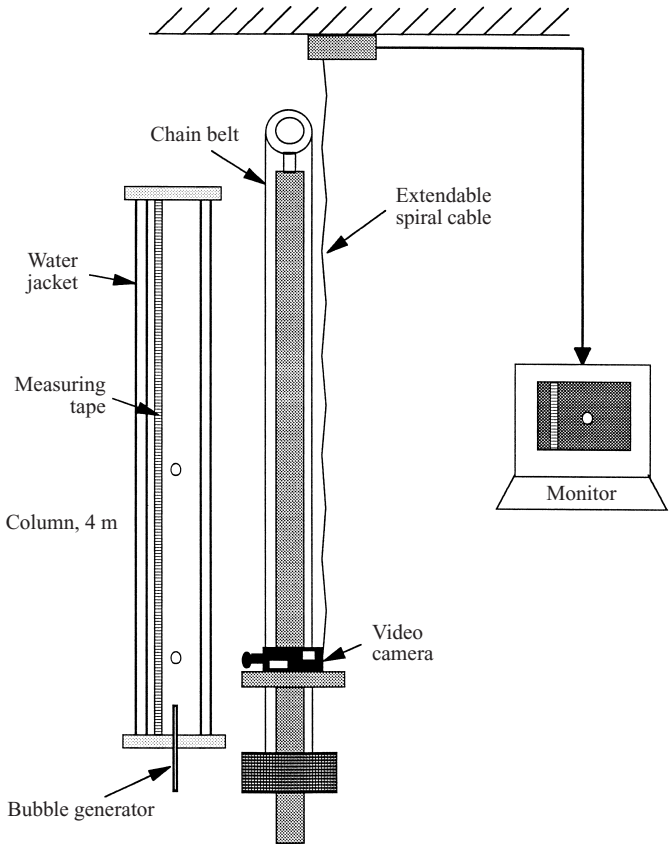


FIGURE 1. Experimental set-up.

C (mol/m^3) $\times 10^5$	Distance (cm)	Steady-state velocity (cm s^{-1}) Present work	F/D (approximate)
		Bubble 1.4 mm diameter	
5.0	> 370	< 15.3	32
12.5	233	14.8	30
74.9	44	14.8	16
		Bubble 0.8 mm diameter	
2.5	> 370	< 11	16
12.5	133	10	11
74.9	42	10	9

TABLE 1. Distance to reach steady-state velocity in the present work and comparison of steady-state velocity data with that of Fdhila & Duineveld (F/D).

Figure 2 shows the rise velocity of 1.4 mm and 0.8 mm diameter (at the release point) bubbles in Triton X-100 solutions at three concentrations. The concentrations are far below the critical micelle concentration of 0.23 mol m^{-3} (Stebe & Maldarelli 1994). At the two higher concentrations the bubbles reach the same steady-state

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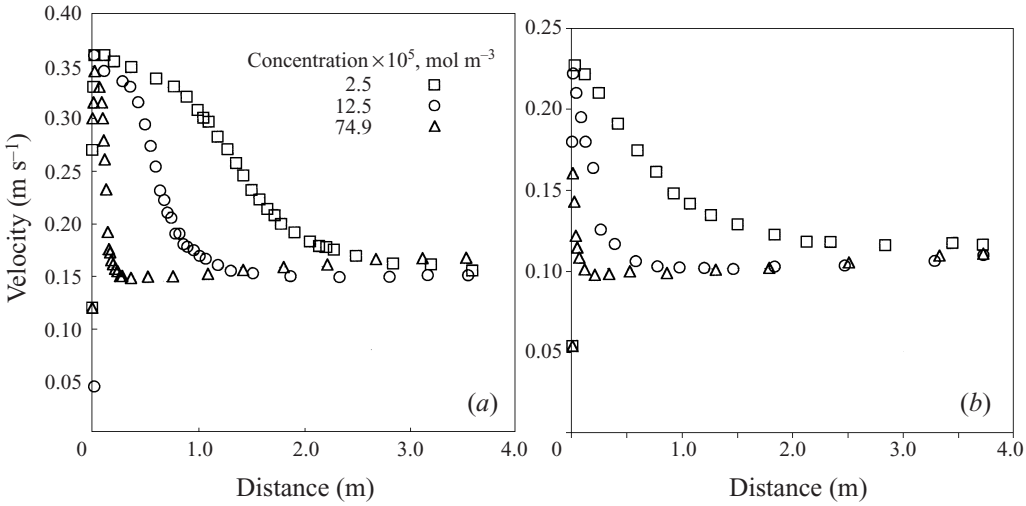


FIGURE 2. Experimental single bubble velocity profiles in Triton X-100 solutions for (*a*) a 1.4 mm bubble and (*b*) a 0.8 mm bubble.

velocity (ignoring bubble expansion effects) while for the lowest concentration, the velocity is still decreasing but apparently approaching the same steady-state value. Table 1 gives the distance to reach steady-state velocity for the two bubbles and compares the steady-state velocity with the measurements of Fdhila & Duineveld (read from their figure 2*a*). It is evident that considerable distance is required to reach the steady-state velocity at these low concentrations and rather than being a function of concentration, the steady-state velocity appears to be constant.

The distance to reach steady-state velocity may be influenced by the bubble generation technique. In our case the bubble is released with negligible initial velocity by the buoyancy force. (One variation, holding the bubble in place on the capillary tip for up to 3 minutes did not alter the velocity–distance result.) Regardless of bubble generation method, however, to ensure steady state is reached it is best to measure the velocity–distance (or time) profile. Using this approach, the evidence in table 1 and that presented elsewhere for different surfactants (Zhang & Finch 1999), indicates that the steady-state velocity does not depend on surfactant concentration over the range we have tested. For Triton X-100 the lowest concentration used was 2.5×10^{-5} mol m^{-3} as below this value impurities in the water caused repeatability to deteriorate. The maximum concentration used was 6.7×10^{-2} mol m^{-3} in the case of the 1.4 mm bubble and the steady-state velocity was 14.3 cm s^{-1}, i.e. essentially unchanged. The fact that the same velocity is reached regardless of concentration suggests that the stagnant cap angle on the bubble is the same at steady state and is not a function of concentration.

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