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The residence time of air bubbles <400 μm diameter at the surface of distilled water and seawater

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ABSTRACT

Air bubbles from 50 to 400 μm diameter were produced from a fine capillary tip inserted through the top of a rotating tank of water. Bubble persistence on the surface was measured from the tank geometry and rotation rate, the minimum detectable time being 10^{-2} s. In distilled water, nearly all bubbles >200 μm diameter persisted <0.05 s, but smaller bubbles existed for several seconds or more. Opposite results were found in seawater. Bubbles less than about 80 μm diameter existed $\leqslant 10^{-2}$ s. For larger bubbles, the residence time increased with size, reaching about 0.3 s for bubble diameters of 300 μm. These results, plus other experiments, suggest that bubble collisions in seawater will produce coalescence if one of the bubbles is less than about 80 μm diameter.

1. Introduction

Approximately 1% of the surface of the World Ocean is continuously covered by whitecaps (Monahan and O'Muircheartaigh, 1980; Cipriano and Blanchard, 1982). The bursting of the whitecap-produced bubbles, a major source of the sea-salt aerosol, is estimated to produce between 10^9 and 10^{10} metric tons of sea salt per year (Blanchard, 1963). The sea-salt is ejected into the air both by film drops from the ruptured film and jet drops from the breakup of the vertically rising jet of water from the collapsing bubble cavity. Since the sizes and numbers of these drops is a function of bubble size, which can increase with time as bubbles coalesce without bursting at the surface of the sea, a knowledge of the time a bubble persists at the surface may be useful for estimates of sea-salt production.

We report here on measurements of the bubble surface life, BSL, the time interval between the arrival of a bubble at the surface and bursting, for bubbles <400 μm diameter at the surface of both seawater and distilled water. In the wide spectrum of bubbles produced by a breaking wave, these small bubbles have the highest concentration (Blanchard and Woodcock, 1957; Monahan and Zietlow, 1969; Cipriano and Blanchard, 1981). This work treats only one factor of the many known to control the BSL. Among others are surface-active material (Garrett, 1967), surface tension gradients (Burger and Blanchard, 1983), and the time spent by the bubble in rising through the water (Blanchard and Syzdek, 1982).

2. Experimental design

All experiments were performed with a tank of water in solid rotation (Blanchard and Syzdek, 1972; Tedesco and Blanchard, 1979). The rotating tank was used for several reasons: (i) it is the easiest way to produce bubbles <500 μm diameter; (ii) it produces uniformly-sized bubbles at a rate of 5 to 50 s^{-1}; (iii) it allows each bubble to rise to a fixed point on the surface in non-rotating laboratory coordinates; (iv) it allows time measurements for rise speed and BSL to be obtained by a geometric approach. This eliminates reaction time errors that are found when a stopwatch is used for direct time measurement.

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The geometric technique used to measure bubble rise speed (from which bubble diameter is obtained) and BSL is shown in Fig. 1. The rotation time of the tank, T, is measured by a stopwatch to within 0.1 s. It is maintained between 7 and 22 s per revolution. The capillary tip, which is drawn out to an inner diameter of approximately 2.5–4.0 μm, is inserted to a depth, H, below the surface of the water. The bubble size is a function of the tip diameter, the air pressure supplied to the tip, and the speed at which the water flows by it. Details of the preparation of bubble-producing capillary tips can be found elsewhere (Blanchard and Syzdek, 1977). Bubbles released from the tip, E, travel to the surface of the water at B. If they have any BSL, they will be carried by the water to burst at C.

The time required for the bubbles to move from E to B, must be equal to the time it takes the water to rotate from A to B. A is the point on the surface

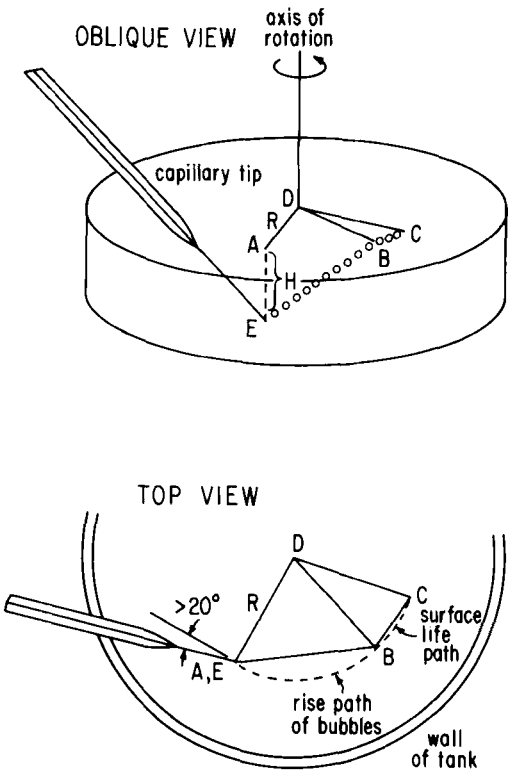

Fig. 1. Schematic diagram of the rotating tank that illustrates the geometrical technique to obtain both the diameter and the residence time of an air bubble at the surface of the water. See details in text.

to which the bubbles would rise vertically from the tip, E, if the tank were stationary. The radius, R, is denoted by lines $\overline{AD}$, $\overline{BD}$, and $\overline{CD}$, the distance of the capillary tip from the axis of rotation (the center of the tank). Thus, the circumference of the circular path the bubbles follow is $2\pi R$. The rise speed of the bubbles, V, is then $H/(\overline{AB}/2\pi R)T$. Similarly, the BSL can be expressed as $(\overline{BC}/2\pi R)T$, where $\overline{BC}$ is the distance the bubbles travel with the surface water before bursting. There is a negligible error, discussed below, introduced by using chord lengths $\overline{AB}$ and $\overline{BC}$ and not the respective arc lengths.

Our rotating tank was a Petri dish of 14 cm diameter and 1.5 cm high. The dish was carefully centered on the turntable and filled with water that was allowed to overflow (overflowing was done periodically during the experiment to eliminate any surface-active contamination). The capillary tip was adjusted to enter the water at an angle of 30 to 40° from the vertical and inward about 20° to 45° from being parallel to the water motion at E. This inward orientation was necessary to avoid wake effects on rising bubbles and interference with those still resting on the surface after one revolution. The tip was positioned between 4 and 6 cm from the axis of rotation and at a depth of 0.3 to 1.0 cm. The depth was measured by a cathetometer to within $\pm$ 0.02 cm.

A light beam from a 35 mm slide projector was used to illuminate the bubbles. They are highly visible in forward and side scattered light. A black background placed behind the rotating system and 180° from the observer line of sight provided maximum contrast. The radius, R, was determined with the cathetometer by measuring the distance from E to the edge of the Petri dish and subtracting this from the known radius of the dish. The accuracy of the measurement is $\pm$0.05 cm.

To measure $\overline{AB}$, a horizontally-mounted cathetometer with a vertically-positioned cross hair on the telescope was sighted to line up exactly with the end of the capillary tip (point E or A on the surface). This reading recorded, the telescope was then sighted so the cross hair was on point B where the bubbles reached the surface. The difference in the readings is $\overline{AB}$. The axis of the telescope was tilted slightly upward. Had the telescope axis been horizontal, the precise location at which the bubbles arrived at B could not have been obtained; curvature of the water meniscus at the edge of the

dish obscured the last 0.2 cm of bubble rise. Looking upward through the sides of the dish, we could see the bubbles approach and make contact with the surface. The exact point of contact was easily determined since the water surface acted like a mirror, each bubble producing a mirror image. The mirror images were enhanced by inserting a wetted piece of black paper below the Petri dish. The bubbles and their images formed a well-defined sideways V-shaped pattern. The apex of the V, point B, is where the bubbles coincided with their mirror images. The length of the line of bubbles extending to the right, $\overline{BC}$, is a measure of the BSL. The smallest measurable $\overline{BC}$ was ~0.3 mm, corresponding to a minimum detectable BSL of $\sim 10^{-2}$ s.

The maximum length of $\overline{AB}$ or $\overline{BC}$ (to which the straight-line measurement was applied) was 4.5 cm. Using this chord length in lieu of the arc resulted in an error of 5% when compared to the more accurate, arc-measurement method described by Tedesco and Blanchard (1979). However, this 5% error changed the calculated rise speed by only about 0.02 cm s^{-1}, thereby affecting calculated bubble size (from Stokes law) by only 3 to 4 μm. Beyond $\overline{AB}$ and $\overline{BC}$ chord lengths of 4.5 cm, arc errors become more substantial, and the arc-measurement method used by the aforementioned was used.

No measurements were made until the water was in solid rotation, at which time a steady state bubble production rate had been obtained. For the geometry used here, solid rotation required 42 to 75 s for rotation times of 7 to 22 s per revolution (Greenspan and Howard, 1968).

Several types of water were used, but most of the experiments were done with distilled water and seawater from the Sargasso Sea. The water temperature was assumed to be the same as the ambient air temperature, which varied from 18° to 20°C. The distilled water, which was passed through the Milli Q^R filtration system, had a resistivity of >18 megohms · cm and a maximum organic content of 0.1 p.p.m. Final filtration removed all particles >0.22 μm diameter. The seawater was collected from 50 m below the surface of the Sargasso Sea. Experiments have also been performed with a 3% NaCl solution and with seawater from Old Orchard Beach (near Portland, Maine).

Many of the experiments were carried out with unfiltered air directly from an air compressor. To insure that contaminants in the air were not affecting the BSL, some of the experiments were carried out with air that had passed through an activated charcoal filter. Argon was used to produce bubbles in some of the work. Negligible differences in BSL were found between these methods of bubble production.

3. Cleaning procedure

The three pieces of equipment coming into contact with the water were the capillary tip, a glass beaker that held excess water used for overflowing, and the Petri dish. Before each experiment, the glass beaker and the Petri dish were soaked for at least 15 min in hot Ivory® detergent solution, followed by a 5 min scrubbing of each item. They were rinsed several times, first in tap water and then in distilled water. The beaker and the Petri dish were soaked in chromic acid prior to several of the experiments, but this produced no apparent difference in the results. Therefore, the simple cleaning procedure mentioned above was used prior to most of the experiments.

Before use, the capillary tip was partially immersed in a beaker of distilled water while air was forced through it. A paper towel was used to gently wipe the tip clean. Occasionally the tip was immersed in chromic acid before rinsing in distilled water. The BSL was the same regardless of how the tip was cleaned.

4. Results

Results are shown in Figs. 2 and 3. Each data point represents observations on BSL from 100 to 1000 bubbles. In distilled water (Fig. 2), nearly all bubbles >200 μm diameter have a BSL <0.05 s. For bubbles <200 μm diameter, however, the BSL increases extremely rapidly with decreasing bubble size. It is about 0.3 s for an 80 μm diameter bubble, but 100 times that, about 30 s (not shown on Fig. 2), for a 60 μm diameter bubble. When the BSL was greater than about 10 s, bubbles did not burst, but slowly disappeared as they went into solution. These small bubbles formed thread-like lines on the surface that existed in complete rings for several revolutions of the dish. There was no apparent coalescence of bubbles. This experiment was

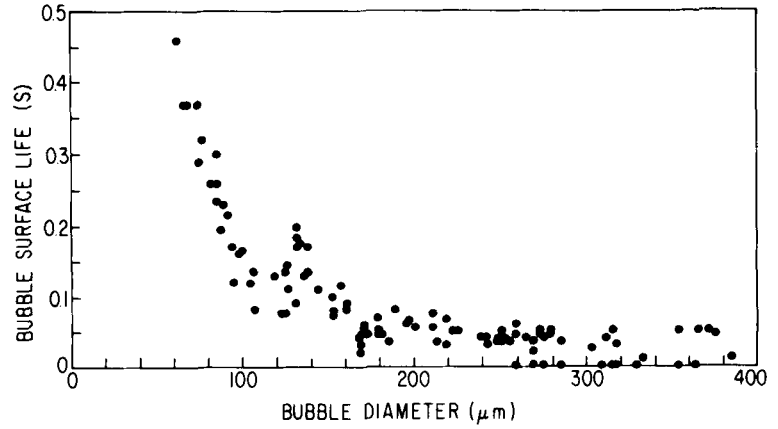

Fig. 2. The residence time (bubble surface life) of an air bubble at the surface of distilled water.

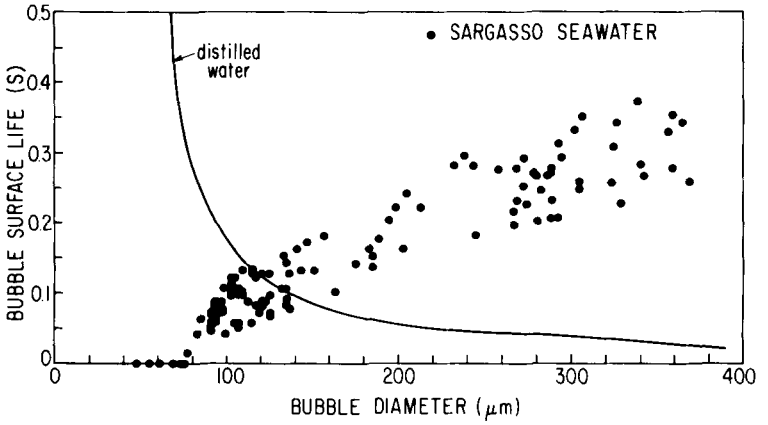

Fig. 3. The residence time (bubble surface life) of an air bubble at the surface of seawater obtained in the Sargasso Sea. The best-fit line for the distilled water data of Fig. 2 has been superimposed.

repeated many times. Similar observations of this curious dependence of the BSL on diameter were obtained with a microscope in a non-rotating system using bubbles produced from a vibrating tip (Struthwolf, 1983).

Results from the Sargasso seawater experiments (Fig. 3) were the opposite of those from the distilled water experiments. For bubble diameters of 100 μm, the BSL averaged about 0.08 s, but increased with bubble size to about 0.3 s for bubble diameters of 300 μm. For bubble diameters <80 μm, the BSL was $\leqslant 10^{-2}$ s. As stated earlier, each data point in Fig. 3 is an average of many observations, but the maximum and minimum deviations did not depart more than about 25% from the average.

The results from the 3% NaCl solution and the Old Orchard Beach seawater were similar to the Sargasso seawater experiments in that the BSL increased with bubble size for bubble diameters >100 μm, but the data points for the Old Orchard seawater were about 30% higher, and those for the NaCl solution about 30% lower, than those for the Sargasso seawater. However, for all three saline solutions, the BSL was $\leqslant 10^{-2}$ s for bubbles less than about 80 μm diameter.

5. Discussion

Pure liquids do not foam. Laboratory distilled water is not necessarily a pure liquid; it takes an

extraordinary effort to remove minute traces of impurities from distilled water to make it non-foaming (Bikerman, 1973; MacIntyre, 1974). Our data for bubbles larger than about 100 μm diameter suggest that our water was pure, for the bubbles persisted at the surface less than 0.1 s. However, the smallest bubbles persisted for many seconds. This suggests that some impurities were present. On the other hand, we know of no other data on the surface life of such small bubbles in distilled water. Until others repeat these experiments we must leave open the possibility that for reasons unknown, bubbles <100 μm diameter can have a surface life of several seconds on pure distilled water.

It is well-known that bubbles in seawater and other saline solutions do not easily coalesce upon contact and can persist for many seconds at the surface (Blanchard and Woodcock, 1957; Lessard and Zieminski, 1971; Scott, 1975). Zheng et al. (1983) and Gluhosky (1983) found that the bubble surface life in seawater is a function of bubble diameter, with the surface life increasing with diameter to a maximum in the millimeter size range and decreasing after that. But neither of these studies were extended to bubbles <1 mm diameter; it is an extrapolation of their data that suggests that the surface life decreases to near zero for very small bubbles.

Bikerman (1968) carried out the only experiments we are aware of on the surface life of bubbles <600 μm diameter in saline solutions. He used aqueous solutions of many salts, including NaCl and KCl, and found that the bubble surface life was almost independent of the salt used. It increased about two-fold as the NaCl concentration went from 1.2 to 20%. Bikerman found that the bubble surface life was constant at about 0.1 s for bubble diameters from 60 to 600 μm, but about a second or more for bubble diameters of 800 to 1300 μm. His data base was not nearly as extensive as that in the present work, but his results are in agreement with those presented here.

Why is it that in our experiments with two samples of seawater obtained at widely different locations, and with the 3% NaCl solution, the persistence of air bubbles at the surface decreased with bubble size to about 0.1 s at a bubble diameter of 100 μm and to $\leqslant 10^{-2}$ s for bubble diameters less than about 80 μm? Though it was not measured, the concentration of dissolved organic matter probably varied by a factor of 5 or greater among these saline solutions. This suggests that organic impurities are not important here, but that the bubble geometry is. It may be that capillary suction (Bikerman, 1973) causes the smallest bubbles to burst more rapidly than the larger ones. The dome of water above a bubble at rest at the surface must thin sufficiently before it can rupture. Regardless of the exact value of the radius of curvature, R_d, of this dome, it probably decreases as the bubble gets smaller. Thus the capillary pressure, $2\gamma/R_d$, where γ is the surface tension, in the thin film of water above the bubble increases with decreasing bubble size. A horizontal pressure gradient is produced, since the capillary pressure decreases and may go slightly negative as we move horizontally away from the bubble dome or film. This pressure gradient will be larger for the smaller bubbles, causing their films to thin more rapidly than those of the larger bubbles, and so their surface life should be less. Similar reasoning was used by MacIntyre (1972) to explain the pressure gradient that drives the surface flow to produce a jet in a bursting bubble. We are aware that the capillary suction argument should apply equally well to small bubbles in distilled water and are at a loss to explain why they do not also burst quickly. If traces of surface-active contamination prevent the bursting of the distilled water bubbles, then why does it not do the same in seawater?

The short surface life for small bubbles has implications for the coalescence of bubbles in seawater. The bursting of a small bubble within 10^{-2} s after arrival at the surface is the same as the coalescence of a small bubble with a bubble of infinite radius within 10^{-2} s after collision. But perhaps the larger bubble need not be of infinite radius for coalescence to occur. With this in mind, we blew a hemispherical bubble of about 5 mm diameter at the end of a pipette that was held end down in seawater. With a vibrating capillary a few centimeters beneath the large bubble, we generated a stream of small bubbles less than 80 μm diameter and let the stream rise upward to collide with the hemispherical bubble. Coalescence occurred immediately if the small bubbles collided head on with the larger bubble or within a certain area on the lower part of the bubble, but when the stream of small bubbles was moved horizontally to collide at a glancing angle at the edge of the larger bubble, no coalescence took place.

Experiments of this nature should be more rigorously pursued since bubbles less than 80 μm diameter are an important part of the bubble spectrum produced by breaking waves (Johnson and Cooke, 1979; Cipriano and Blanchard, 1981). At this point it is becoming clear that the oft-quoted statement that air bubbles do not coalesce upon collision in seawater is true only for bubbles larger than about 80 μm diameter.

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