NOTES AND CORRESPONDENCE

Temperature Effects on Generation and Entrainment of Bubbles Induced by a Water Jet

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ABSTRACT

A simple experiment simulating the jet feature of breaking waves is conducted to study quantitative effects of the water temperature on the generation of bubbles at the air-water interface and their entrainment into the water column. The results indicate that there is a critical water temperature for the inception of bubbles. Such a critical temperature can be attributed to changes of the surface tension and viscosity, both of which decrease as water temperature increases. Field measurements of the bubble entrainment depth, bubble size spectrum, and whitecap coverage are shown to have similar temperature dependencies as our observations.

1. Introduction

Bubbles in the ocean scatter acoustic waves (Brekhovskikh and Lysanov 1982) and produce marine aerosols in the atmospheric surface layer (Blanchard and Woodcock 1957). During their rise in the water column, bubbles can effectively scavenge organic materials and bacteria to transport them to the sea surface (Blanchard 1981). This process is important in the air–sea gas exchange and the formation of films on the ocean surface. Much has been discussed on the vertical distribution and size composition of bubbles (Wu 1981, 1988a; Thorpe 1982, 1986; Baldy and Bourguel 1987; Hwang et al. 1990), but basic mechanisms of the bubble generation at the sea surface and their entrainment into the water column are still not well understood. Koga (1982) showed the jet feature of bubble plume under breaking waves; similar features were also reported by Bonmarin (1989).

Direct measurements of oceanic bubbles (Kolovayev 1976; Johnson and Cooke 1979; Thorpe 1986) and related observations of whitecap coverages (Monahan 1971; Monahan et al. 1981, 1985; Doyle 1984; Monahan and O'Muircheartaigh 1980, 1986) display some interesting temperature dependencies. In particular, Thorpe's data showed that the bubble entrainment depth in the winter season was consistently smaller than that in the fall (Hwang et al. 1990). Similarly, the whitecap coverage was found to be larger in warmer waters under otherwise similar environmental conditions (Wu 1988b). The bubble size spectra of Johnson and Cooke (1979) in cold water with temperatures between 2° and 3°C were also shown to be much narrower than Kolovayev's (1976) obtained at an average temperature of 14°C.

In order to verify the effects of water temperature on bubble generation, a simple experiment was conducted to simulate the jet feature of breaking waves. Water jets were directed at a fixed angle (45°) onto a receiving water body. Remarkable variations of bubble formation and entrainment were found at different water temperatures. With the present setup, bubbles were not generated when the water temperature was below 10°C, were intermittently generated at around 10°–11°C, and were always generated at higher temperatures. The penetration depth of bubbles increased with the temperature until 19°C, and remained roughly constant from thereon.

2. Experimental setup

A water jet from a small pipet with a 1.75-mm inner diameter was discharged at an inclination of 45° into a receiving reservoir ($0.6 \times 0.3 \times 0.3$ m^3). Both the supply tank and receiving reservoir have overflowing openings to maintain constant heads. The vertical distance of the jet exit to the overflowing, receiving water surface was 6.5 cm. Hot and cold tap waters were mixed with ice to produce a desired temperature from 5° to 40°C for both the supply and receiving tanks. The air temperature was not controlled. In a later trial, a plastic cover was placed above the receiving tank, and the air temperature was maintained to be close to the water temperature by either ice cooling or hot-air heating. No significant influence, however, was found in the bubble generation process due to the air-temperature control. The velocity of the water jet was controlled by the water level of the overflowing supply tank. The

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flow rate was calibrated by measuring the time to collect one liter of water from the jet. This procedure proved to be repeatable with an accuracy of within 3%, and the flow rate was constant within the above temperature range.

Rulers with a millimeter scale were placed on the top, middle, and side of the receiving tank. The depth of bubble penetration was observed visually and supplemented by snapshots with a 35-mm camera. The penetration depth is defined as the depth of the trough of the bubble plume. It was found that even under a constant waterhead, the penetration depth, concentration, and size of bubbles were not invariant of time; therefore, the snapshots were used only as a reference. The major results to be presented are based on visual observations over a period of approximately 1 to 2 minutes for each temperature change.

3. Results

The experimental conditions are listed in Table 1, in which T_1 and T_2 are the water temperatures in the supply and receiving tanks, respectively, and h is the penetration depth of bubbles. When entrainment occurred, the bubbles were visually observed to be roughly divided into two groups according to their sizes. Larger bubbles, with diameter greater than 1 mm, penetrated to only a shallow depth. Rising back to the water surface, these bubbles produced disturbances (the bubbling water) at the water surface. A second group of much smaller bubbles, as small as 0.1 mm, were carried to a much greater depth. These depths, generally fluctuating in the range of approximately ±0.02 m, are tabulated in Table 1 and plotted in Fig. 1. With the present experimental condition, bubbles were not generated when the water temperature was below 10°C, and only intermittently generated at water temperatures slightly above 10°C (Table 1). The generation became continuous when the water temperature reached 11°C. Between 11° and 17°C, the penetration depth of small bubbles showed a gradual increase from 0.09 to 0.14 m; while between 19° and 36°C, there

TABLE 1. Experimental conditions. (Jet velocity: 2.08 m s^{-1})

Run	T_1 (°C)	T_2 (°C)	$\frac{VD}{\nu}$	$\frac{V}{(g\nu)^{1/3}}$	$\frac{h}{(m)}$
1	4 ~ 9	4 ~ 9	<2700	<88	No bubbles
2	10.0	9.0	2780	88.8	Intermittent
3	11.6	10.6	2830	89.4	0.09
4	11.9	11.8	2860	89.7	0.09
5	15.3	15.3	3200	93.1	0.12
6	17.0	16.7	3390	94.4	0.14
7	18.9	18.2	3520	96.1	0.22
8	22.6	22.3	3780	97.9	0.26
9	26.9	26.8	4250	102.0	0.25
10	31.3	31.5	4700	105.7	0.26
11	35.9	35.9	5100	108.8	0.26

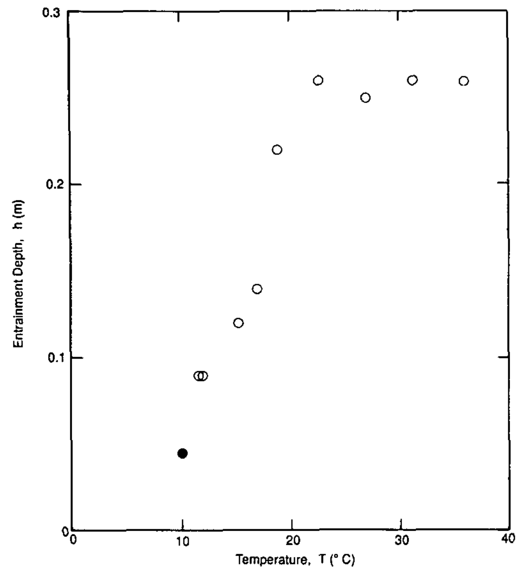

FIG. 1. Temperature dependence of bubble entrainment depth. The solid symbol represents intermittent bubble production.

was no discernable difference of the bubble structure, and the penetration depth was nearly constant.

4. Discussion

a. Parameters contributing to the temperature effect

Our simple experiment demonstrated successfully that there were significant temperature effects on the generation and penetration of bubbles induced by a water jet. The most interesting observations are those at lower temperatures (<10°C), where the bubble generation is hindered. Koga (1982) demonstrated that the critical angle for bubble production by a water jet was governed by the surface tension and jet velocity. These two parameters can be combined into the Weber number, $W_e = V^2 D/\sigma$, where σ is the surface tension of water, and V and D are respectively the velocity and length scales of the water jet. Detsch and Sharma (1990) conducted a more extensive study of the critical angle. They varied the pipet geometry, jet velocity, and distance between jet and water surfaces, and used different fluids. It was found, among other results, that the viscosity of fluid also played an important role in the bubble production. The dimensionless parameter combining the viscosity and the jet velocity can be in the form of a Reynolds number, VD/ν. If the gravitational restoration is considered as a balance factor, it can be written as $V/(g\nu)^{1/3}$, where g is the gravitational acceleration. The length scale used here is the jet diameter, but it can also be a length of the wedge-shaped air cavity that is formed by the convergence of surface flows around the jet. The former dimensionless parameter represents the degree of flow disturbances and governs the force exerted on the air cavity; the latter represents the balance between the jet impinging at the water surface and the buoyancy resistance to the air penetration. The computed values of VD/ν and $V/(g\nu)^{1/3}$ are listed in Table 1. The dependence of entrainment depth on these two dimensionless parameters are shown in Fig. 2. The condition for a continuous bubble generation under the current experimental configuration occurs at $VD/\nu > 2800$ or $V/(g\nu)^{1/3} > 89$. The bubbles are not generated when $VD/\nu < 2700$ or $V/(g\nu)^{1/3} < 88$.

b. *Comparison with other observations*

1) Bubble spectrum

Kolovayev (1976) operated a bubble trap away from a ship to obtain bubble size distribution in the subtropical Atlantic Ocean, where the water temperature was uniform from the sea surface down to a depth of 25 m and averaged 14°C. The wind velocities encountered were from 6 to 13 m s^{-1}. Johnson and Cooke (1979) used a camera suspended from a float to capture bubbles in the water column in a coastal area where the water temperature was between 2° and 3°C. The wind velocities were from 8 to 13 m s^{-1}. Their results were discussed extensively in Wu (1981, 1988a). In particular, the size spectra measured in cold water by Johnson and Cooke have a much narrower size range as compared to Kolovayev's measurements in warm water (Fig. 10, Johnson and Cooke 1979). The broadening of the bubble size spectrum at higher temperatures is consistent with our observation that the bubble production is enhanced in warm water.

2) Bubble penetration depth

Thorpe (1986) measured the structure of a bubble plume by an acoustic instrument in the ocean (Station DB2) during fall (September–October 1984) and winter (December 1984–January 1985) seasons. The bubble entrainment depth, defined as the *e*-folding depth of the acoustic backscatter cross section (reflecting the bubble concentration), were reported. A systematic difference was found between the entrainment depths measured in the two seasons (Fig. 3, Hwang et al. 1990). Typically, the depths in winter were approximately half of the fall values. The temperatures reported were 14.7°–17°C in the fall and 10.7°–11.6°C in the winter. This temperature dependence is consistent with our experimental results that bubble generation was hindered at low water temperatures and that major changes were found to occur at a temperature of approximately 11°C.

3) Whitecap coverage

Data of whitecap coverages were obtained from a wide range of environmental conditions (Monahan 1971; Monahan et al. 1981; Doyle 1984; Monahan et al. 1985). Of special interest here is the temperature factor analyzed by Wu (Fig. 3, 1988b). The whitecap coverage at near-zero temperatures was shown to be considerably less than that in warmer water. Whitecaps are produced by breaking waves and the returning of breaking-generated bubbles to the water surface; in other words, the extent and persistence of whitecap patches are related to the generation and entrainment of bubbles. The observed reduction of whitecap coverage at a lower temperature is consistent with our results that a lower water temperature hinders the bubble generation. Monahan and O'Muircheartaigh (1986) also stated that a higher water temperature or an unstable interfacial condition enhanced whitecap production and reduced the minimum wind speed for whitecap generation.

4) Bubble size and density

Pounder (1986) reported that the bubble density increased with temperature from 1.1° to 28.9°C, and the size of bubbles decreased as temperature increased. The trend found in the present experiment, that the water surface became more penetrable as the temperature increased, is qualitatively similar to Pounder's results.

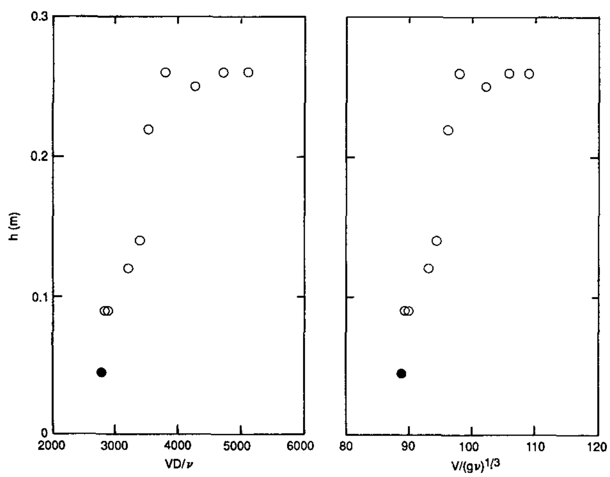

FIG. 2. Variations of entrainment depth with dimensionless parameters, VD/ν and $V/(g\nu)^{1/3}$. The solid symbol represents intermittent bubble production.

5. Conclusion

Our simple experiment has demonstrated clearly that low water temperatures hinder the production of air bubbles and their downward entrainment. The critical temperature for continuous bubble production under the present experimental condition is 11°C. The penetration depth increases monotonically with water temperature, but reaches an asymptotic value at higher water temperatures. These results are consistent with the temperature dependence found in the field observations of bubble size distribution, entrainment depth, and whitecap coverage.

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