Chapter 8

CONCLUSIONS

A systematic laboratory study on bubble clouds characteristics under various conditions – wind speed, water temperature and salinity – was conducted. Imaging technique was employed.

Bubble clouds were video recorded for 15 minutes at three different water temperatures (13, 20 and 27°C) in two plane views, side and top. Each of these six experiments was conducted for wind speeds from 9 to 16 m s^{-1}. In addition, for each experiment video records with a small field of view registered the individual bubbles within the clouds. Complementary measurements of water surface elevation were made with a wave gauge in order to obtain the wave characteristics –frequency, period, length and phase speed – for scaling the bubble cloud parameters. From the video records up to ten sequences of bubble cloud events, each consisting of about 30 images, were digitized at time interval of 33 ms for wind speeds 10, 12, 13, 14, and 16 m s^{-1} and for side and top views. Bubble cloud characteristics – length, thickness, depth of penetration, width, and void fraction – were extracted from the images. Temporal and spatial changes of these characteristics, and their statistical features, were explored. Wind and temperature dependencies were quantified.

The influence of the water salinity on bubbles' and bubble clouds' characteristics was also experimentally investigated. Single bubbles were produced by forcing air through a capillary tube in saline water. Clouds of bubbles in water with varying values of salinity were produced with a water jet with the corresponding salinity. Both pure and contaminated water were used. Besides salinity, the surface tension and the water temperature were strictly controlled. For a single bubble the bubble diameter, rise velocity and surface lifetime were of interest. For clouds of bubbles the number of bubbles within, the shape, the penetration depth and the void fraction of the cloud were explored.

The results of this study can be summarized in the following conclusions:

1) Once formed, the bubble clouds grow and decay through a group of plumes for about one wave period. The temporal variations of all bubble cloud characteristics (length, thickness, depth of penetration, width, and void fraction) reflect this process by passing through a maximum and decreasing to some small and stable values.

2) The duration of the whole process – formation, growth and decay – varies considerably within the one-wave-period time span and does not exhibit consistent trends with the increase of wind speed. That is, at lowest (10 m s^{-1}) and highest (16 m s^{-1}) winds equally short, of order of 0.6T, and long, one wave period T, time evolutions are possible. An explanation of this result is that the wave field consists of a band of wave frequencies around the dominant wave peak, which slightly moves toward lower value with increasing the wind.

3) After the active lifetime, about one wave period, the cloud residue with a void fraction of order of 20% joins the background population of stabilized bubbles.

4) The bubble clouds are usually formed at the front slope of the wave within the wave phase range 33 to 57 degree (the wave crest is at 90°) . The stage of cloud growth is related to the wave crest and back associated with wave phases from 45 to 135°. The subsequent decay associates with the wave downward slope and trough, phases from 135 to 300°.

5) Initially the cloud moves horizontally forward with the wave at approximately half the wave phase speed, 0.5c, then its horizontal speed decreases to almost zero in the wave trough. In vertical plane, the initial downward movement of the cloud is quickly decelerated from approximately 0.1c to zero. Then, the wave crest causes an upward motion. The back of the wave pushes the cloud in depth again. The wave forcing is weakest in the wave trough where the cloud assumes an upward velocity of the order of the rise velocity of the bubbles (22 cm s^{-1}) .

6) The probability density functions (PDFs) of the cloud parameters reveal the probability with which a given cloud parameter assumes its possible observable values. These probabilities change with increasing wind. The cloud length covers a range of values from 0.1L to 0.7L, where L is the wave length. The depth of penetration assumes values from $0.5H_s$ to $2H_s$, where H_s is the significant wave height. The cloud void fraction is close to 100% for a time of 0.1T s and decreases to about 20% before the end of the wave period.

7) The PDFs of the cloud parameters are difficult to associate with a known distribution. They are formed by overlapping of the distributions of several physical processes and have very notched form. The separation of the different process is possible for the void fraction, for which the initial and residual stages exhibit well defined separate PDFs. The residual PDF is well fitted with a Rayleigh distribution. Such separation does not improve the perception of the PDFs for the dimensional parameters.

8) The general trend in the bubble cloud characteristics with wind is discerned from the average values of the bubble cloud parameters. The wide variances of these average values should be noted: they reflect the temporal changes of the parameters. The variations of the cloud characteristics with increasing wind can be fitted with power-law equations. The cloud length exhibits the strongest changes. The void fraction stays almost constant at an average value of 63%, which seems reasonable since an increasing volume of air is entrained and spread into increasing cloud volume.

9) The cloud characteristics show very weak temperature dependence. Indeed, there are signs of enhancement of all cloud parameters with increasing the water temperature. However, the changes brought by the different water temperatures are probably masked by the stronger influence on them from the wave field.

10) The size distributions of the individual bubbles within the clouds were obtained. They compare favorably with previous results. The slope of the large bubbles distribution follows a d^{-2} power law. The possibility to calculate the bubble size distribution from the measured void fraction was considered and illustrated with data from the present

study. According to this calculation, the high void fraction (from 100 to 20%) characterizing the initial stage of the bubble clouds are source of millions ($\approx 10^8$) of bubbles of radius 100 μm and thousands ($\approx 10^3$) of millimeter-sized bubbles.

11) The possible implications of the obtained results were evaluated. The cloud penetration depth can be a measure of the turbulence induced by the breaking waves and hence this cloud parameter can be used for inferring the mixing layer.

12) Calculations of the residence time of the bubbles within the cloud and the area that they provide show that the gas exchange is enhanced considerably by the active whitecaps due to the huge amount of small bubbles and the presence of large bubbles, though they are shortly living features.

13) The salinity content of the water does not influence the size of the bubbles and their rise velocity directly. Over a wide range of salinities they remain constant for a bubble of a given size. However, the salinity changes the ionic strength of the water which decreases the coalescence rate in salt water compared to that in fresh water. Hence, the salinity indirectly influences the bubble size distribution in sea water towards smaller-sizes. This makes the underwater part of the whitecaps in the sea more persistent, and greater area available for subsequent gas exchange.

14) The salinity renders an increase of the bubble surface lifetime (tens of seconds) over the range 10-20$^{\circ}/_{oo}$. In fresh water and weak solutions of salt (up to 10$^{\circ}/_{oo}$) as well as in strong solutions (above 25$^{\circ}/_{oo}$) the bubbles live on the surface for less than 2s.

15) The shape of the bubble clouds does not change over a range of water salinities. Whatever the salinity, bubbles of a certain size have always the same depth of

penetration. What changes is the lowest point of the cloud, as with the salinity increase smaller bubbles are generated which penetrate deeper in the water.

16) The number of bubbles generated within the cloud increases with the salinity increase from 0 to about $12^{o}/_{oo}$ and have maximum over the range of salinities 12 - $25^{o}/_{oo}$. Further increase of the salinity decreases the number of bubbles in the cloud. The explanation of this observation is the change of the coalescence rate. For very low and very high salinities the bubble interfaces are less stabilized by organic matter and easily coalesce.

17) The void fraction of the bubble cloud passes through a similar maximum, of order of 40%, over the range of salt concentrations 12 - $25^{o}/_{oo}$.

The bubble winked at me, and said,
"You'll miss me brother, when you're dead."

Oliver Herford 1863 - 1935
Toast: The Bubble Winked