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Laboratory Measurements of Bubble Size Distributions beneath Breaking Waves

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Several investigators have recently compared field measurements of air-sea gas exchange with predictions from a variety of models (Farmer, McNeil and Johnson, 1993 and Wallace and Wirick, 1992). Wallace and Wirick (1992) found that estimates of the air-sea flux of oxygen , based on measurements of the dissolved oxygen (DO), were up to three orders of magnitude greater and in some cases of opposite sign to predictions based on the thin film model and the Liss-Merlivat equations. They observed sudden increases in the DO concentrations followed by gradual decreases. A numerical simulation, in which the conventional thin-film model was coupled with a semi-empirical equation developed by Thorpe (1984) for calculating the gas exchange due to entrained air bubbles, predicted DO time series that were in qualitative agreement with the observations. Based on these results Wallace and Wirick (1992) conclude that the sudden increases in DO were caused by the increased air entrainment associated with breaking waves. Farmer et al (1993) measured a variety of parameters including DO during a storm in the Georgia Strait. They computed oxygen fluxes based on DO measurements and compared them to predictions derived from (a) the thin-film model which does not include the gas transfer due to bubble entrainment, and (b) the model of Woolf and Thorpe (1991) which parameterizes the gas transfer due to bubble entrainment. Both models under predicted the observed DO levels by wide margins. These two studies clearly demonstrate the need for additional fundamental research investigating the effect of air entrainment by breaking waves on air-sea gas transfer.

Keeling (1993) has used a model of bubble-induced gas exchange to investigate the role of large bubbles in air-sea gas exchange. He concluded that bubbles greater than 0.5 mm in radius contribute significantly to bubble-induced air-sea gas exchange. In addition, his results suggest that the majority of the enhanced air-sea gas transfer observed at windspeeds greater than 13 m/s is due to bubble entrainment by breaking waves. However, he noted that there is large degree of uncertainty in predictions of the bubble-induced air-sea gas exchange because of a lack of data on the production rates and size distributions of large bubbles (radius greater than 0.5 mm). We have addressed this issue by conducting a series of laboratory experiments to measure the bubble size distributions produced by mechanically generated breaking waves.

The experiments were conducted in a wave channel located at the Canada Centre for Inland Waters, Burlington, Ontario. The glass walled channel was 10 m long, 30 cm wide and was filled with water to a depth of 40 cm. A computer controlled hinged hydraulic wave paddle was programmed to focus a dispersive wave packet at a point x_b along the channel. This technique has been used previously to investigate the behavior of spilling and plunging deep-water breaking waves (Chan and Melville, 1988). The intensity of the breaking event and the fractional energy dissipated by breaking were controlled by varying the amplitude of the wave packet. A wave packet with a centre frequency of 1.12 Hz and a bandwidth of 0.7 Hz was synthesized from 32 sinusoidal components and focused to break at $x_b = 5.8$ m from the wave paddle.

Experiments were conducted in both fresh and salt water. Measurements of the surface displacement were sampled in fresh water using resistance wire wave gauges. The surface displacement measurements were used to compute the fractional energy dissipated by each breaking event. Breaking events with fractional energy dissipation from 0 to 12% were sampled. Surface displacement measurements were not made in salt water due to technical difficulties and therefore we assumed the dissipation was the same in fresh and salt water. Video recordings of the entrained air bubbles were made through the glass sidewall. The video camera was positioned so that the field of view included the free surface. This allowed us to measure the size of bubbles immediately below the free surface as well as those entrained to deeper depths. The video images were digitized and analyzed to determine the size and location of the bubbles in each image. A typical size distribution under a salt water spilling wave is shown plotted in figure 1. Preliminary results indicate that the slope of the bubble size distribution for bubble radii greater than 0.5 mm is approximately minus three in both salt and fresh water i.e. the number of bubble per wave per unit radius $\propto r^{-3}$. Only a few bubbles larger than 3 mm in radius were observed and the maximum bubble size observed was approximately 5 mm. The resolution and quality of the video images limited the size of the smallest bubbles we could accurately measure to approximately 0.5 mm radius. Therefore, the values plotted in the size bins below 0.5 mm in figure 1 are inaccurate and should be ignored. A plot of the cumulative volume of the same bubble size distribution is shown plotted in figure 2. This figure clearly indicates that the majority of the volume of air is entrained in bubbles with radii between 1 mm and 3 mm.

The variation of the bubble size distribution with the fractional energy dissipation will be discussed. The measurements of the bubble size distributions in fresh and salt water will be compared. In addition, data showing the vertical variation of bubble sizes with depth will also be presented. The relevance of the measurements to air-sea gas exchange will be discussed.

References

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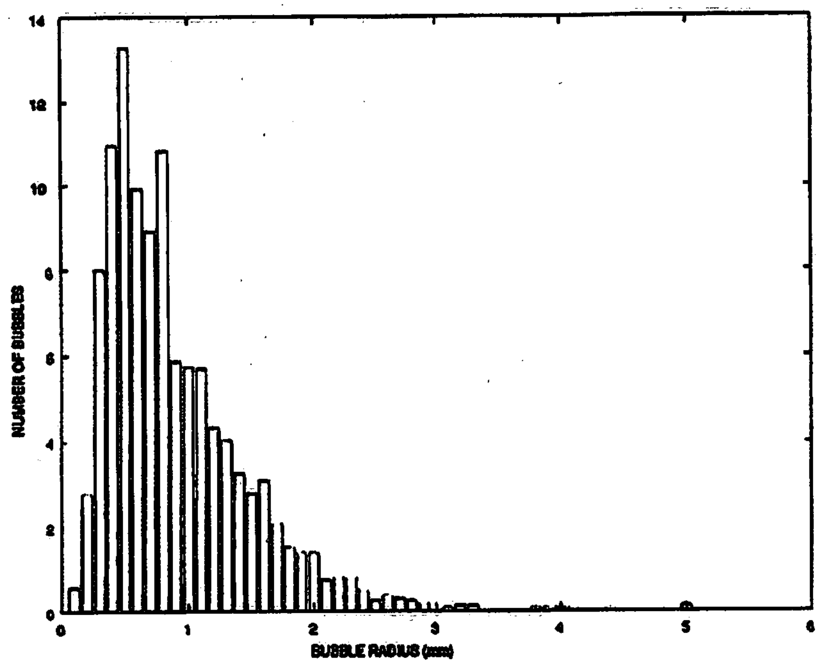

Figure 1: Histogram of bubble sizes in 0.1 mm radius bins. The vertical axis is the number of bubbles per wave per 0.1 mm bin. The data are the result of averaging the data from 16 video images for a breaking wave with a gain, G = 0.76 which corresponds to a fractional energy dissipation of 5%.

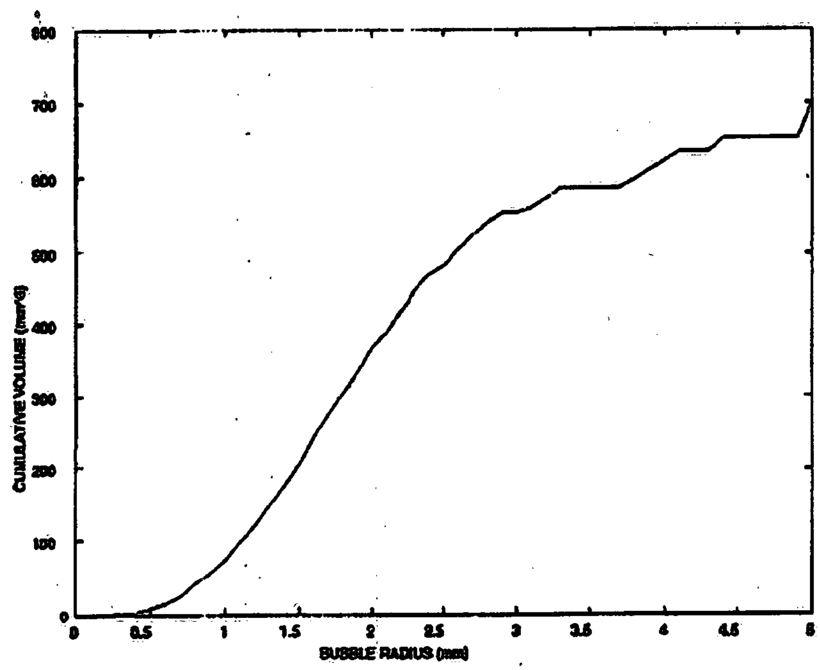

Figure 2: The cumulative volume of the bubble size distribution plotted in figure 1.

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