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LETTER TO THE EDITOR

AN EXPERIMENTAL STUDY ON AIR CARRYUNDER DUE TO A PLUNGING LIQUID JET

The authors would like to congratulate Bonetto & Lahey (1993) for their excellent paper. The article provides interesting information on the size entrained bubbles and on the interactions between air bubbles and turbulence. The authors wish to comment on the definition of "smooth jet" used by the authors. These comments are based upon the authors' observations on a two-dimensional plunging jet experiment. Further, some predictions on the characteristics of air bubbles entrained by "smooth jets" are presented.

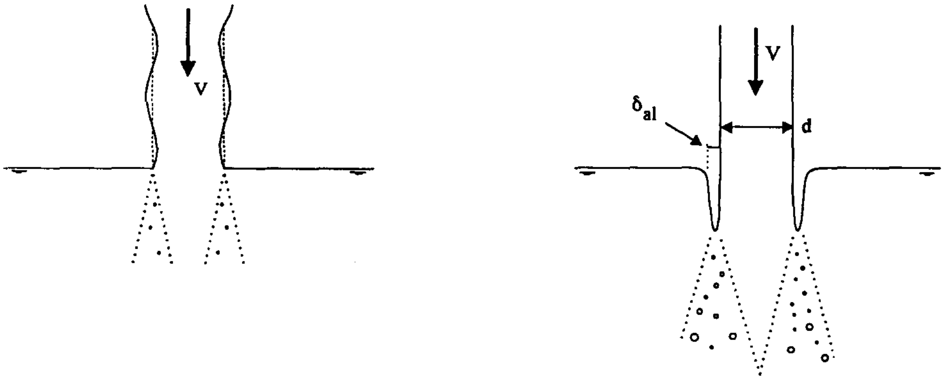
AIR ENTRAINMENT BY A PLUNGING JET

For a "smooth" plunging liquid jet, figure 3 in Bonetto & Lahey (1993) pictures only one type of plunging jet flow pattern (i.e. a high velocity jet).

The present authors performed experiments using a two-dimensional plunging jet. The apparatus consisted of a glass tank with a depth of 1.8 m, a width of 0.30 m and a length of 3.6 m. A PVC rotatable slot nozzle supplied a planar jet, 0.27 m wide and 0.012 m thick. The length of the plate that supported the jet was 0.35 m.

During the present authors' experiments, visual observations (high-speed photographs, high-speed videocamera) indicated that, at low velocities (figure 1), air bubble entrainment is caused by the pool water being unable to follow the undulations of the jet surface (figure 1, left) and small air pockets are formed. Air enters the flow following the passage of these disturbances through the interface between the jet and the receiving fluid. The air entrainment process is intermittent and pulsating.

Figure 2 shows an individual air bubble being entrained on the centreline of a vertical jet. For that experiment, the flow conditions immediately upstream of the impact of the liquid jet with the free surface were: $V = 2.35$ m/s, $\mathrm{Tu} = 0.5\%$ and $d = 3$ mm. High-speed photographs were taken in the dark with a flash speed of 33 μs. The photograph (figure 2) shows the entrainment



Low velocity jet
Intermittent air entrainment

High velocity jet
continuous air entrainment

Figure 1. The mechanisms of bubble entrainment by a plunging jet.

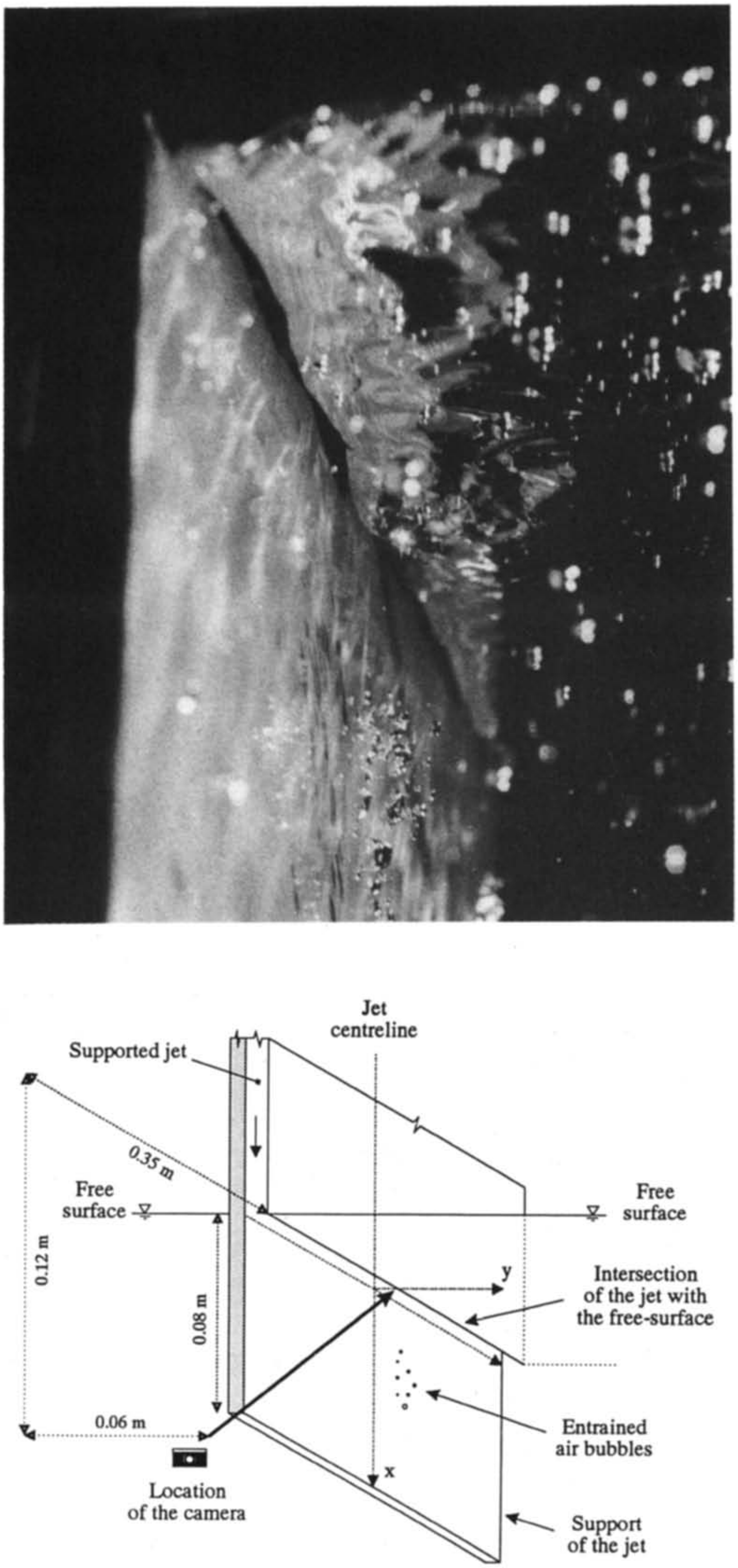


Figure 2. Air bubble entrainment for a low-velocity plunging jet and a sketch explaining the position of the camera.

of individual air bubbles below the intersection of the two-dimensional jet with the free surface. No air sheet is observed.

At larger velocities (i.e. $V > 5$ to 8 m/s), experiments on both circular (Van De Sande & Smith 1973) and planar (the present authors' experiment) plunging jets indicate a qualitative change in the air entrainment process. A thin sheet of air, set into motion by shear forces at the surface of the jet, enters the flow at the impact point, as shown by Bonetto & Lahey's figures 3 and 4a and in figure 1 (right) herein. The air entrainment is characterized by an apparent "continuous" supply of air. The jet velocity at which the air layer appears is an inverse function of jet turbulence: i.e. for "smooth" jets, the air sheet will appear at larger velocities than for "rough" jets.

PREDICTION OF BUBBLE SIZE

Next to the plunge point, a region of high recirculation and energy dissipation is generated, where the entrained air is broken into small bubbles before being transported downward by the water flow. The maximum bubble size d_{m} is determined by the balance between the surface tension forces and the inertial forces caused by the velocity changes over distances of the order of the bubble size. The present authors (Chanson & Cummings 1992) have developed a simple model to predict the maximum bubble size at the end of the developing flow region of the jet. The model is based upon an idealized plunging jet entrainment process shown in figure 3.

For vertical water jets, the maximum bubble size d_{m} can be correlated for low velocity jets as

$$d_{\mathrm{m}} = K_1 \cdot \frac{(\mathrm{We})_{\mathrm{c}}}{V^2}, \qquad [1]$$

where $(\mathrm{We})_{\mathrm{c}}$ is a critical Weber number for bubble splitting, V is the jet velocity at the impact with the free surface of the receiving water and $K_1 = 2.11 \cdot 10^{-4}\,\mathrm{m}^3/\mathrm{s}^2$ for two-dimensional plane jets and $K_1 = 2.74 \cdot 10^{-4}\,\mathrm{m}^3/\mathrm{s}^2$ for circular jets at 20°C and atmospheric pressure. Experiments suggested that $(\mathrm{We})_{\mathrm{c}}$ is a constant near unity. For high-velocity jets, an established air layer is formed at the intersection of the jet and the receiving pool (figure 1, right). The maximum bubble size can be correlated as

$$d_{\mathrm{m}} = K_2 \cdot \sqrt[3]{(\mathrm{We})_{\mathrm{c}}} \cdot \left(\frac{\delta_{al}}{V}\right)^{2/3}, \qquad [2]$$

where δ_{al} is the thickness of the air layer (figure 1, right) and K_2 is a constant of proportionality ($K_2 = 0.0595\,\mathrm{s}^{-2/3}$ for plane jets; $K_2 = 0.0649\,\mathrm{s}^{-2/3}$ for circular jets). There is little information available on the thickness of the air sheet. The photographs and experiments of Bonetto & Lahey (1993) suggest that δ_{al} is in the range 0.5–5 mm.

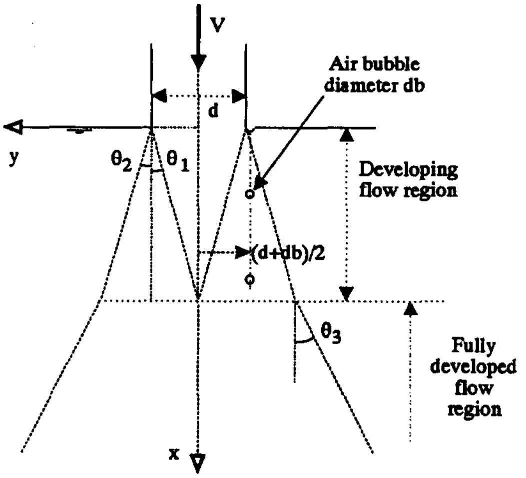


Figure 3. Idealized plunging jet.

For Bonetto & Lahey's (1993) experiment, described in their figures 4 and 5, the jet velocity is 7.0 m/s. Assuming that the air sheet thickness is about 0.5 mm, herein would predict a maximum bubble size of $d_m = 112\,\mu\text{m}$ for $(\text{We})_c = 1$. This result is in agreement with the observations of Bonetto & Lahey (1993, figure 5).

It would be very interesting to know if Bonetto & Lahey were able to estimate the thickness of the air layer from their experiments.

For jet velocities between 2–6 m/s, the present authors observed an air sheet thickness of about 0.5–3 mm. Further, the air sheet behaves as a ventilated cavity (e.g. Laali 1980; Michel 1984): the length of the air layer fluctuates considerably and air pockets are entrained by discontinuous "gusts" at the lower end of the air layer.

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