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MECHANISM OF AIR ENTRAINMENT BY AN IMPINGING LIQUID JET

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ABSTRACT

The process of air entrainment induced by a liquid jet plunging into a mass of relatively quiescent liquid is studied both experimentally and numerically. The experiments show that a smooth jet does not entrap air even at relatively high velocities. When surface disturbances are generated on the jet by a rapid temporary increase of the liquid flow rate, large air cavities are formed. Their collapse under the action of gravity causes the entrapment of bubbles in the liquid. This sequence of events is recorded with a CCD and a high-speed video camera. Analysis of the images of the underwater air cavity indicates that the volume of air entrapped in the liquid is a linear function of the jet disturbance size. Numerical simulations using a boundary integral method support the experimental observations.

INTRODUCTION

The process of air entrainment induced by a liquid jet plunging into a mass of relatively quiescent liquid is encountered very often both in nature and in industrial operations. Pouring water into a tank, breaking waves in the sea and lakes, waterfalls, and weir flows are readily observed to cause the phenomenon. In industrial operations air entrainment may occur, for example, in hydraulic plants, gas-liquid reactors, wastewater treatment plants, and in the course of pouring molten glass or metal. In spite of its commonplace occurrence and engineering importance, air entrainment processes due to impinging liquid jets have received relatively little attention. A detailed review of the work prior to 1993 has been given by Biń (1993); for subsequent work see e.g. Bonetto and Lahey (1993), Oğuz, Prosperetti and Kolaini (1995) and Prosperetti and Oğuz, (1997).

An early study on the mechanism of air entrainment is that by Lin and Donnelly (1966). They found that when the jet speed is high enough, the cause of entrainment is the instability of the jet in the air, i.e. the surface roughness of the jet. This observation was subsequently confirmed by several researchers (e.g. Sene, 1988; Bonetto and Lahey, 1993). Although there is little doubt that disturbances on the jet surface are the main cause of air entrainment, the detailed mechanism of the process has not been investigated. It is unclear how the disturbances on the jet surface affect the entrainment and, once it begins to entrain, how much air is entrapped inside the receiving pool.

This investigation aims to probe the mechanism of air entrainment due to surface roughness. In order to avoid the randomness associated with turbulence generated by the nozzle, a single, well-characterized, and reproducible disturbance is generated on a smooth circular jet.

EXPERIMENTAL DETAILS

The experiment was carried out in a 0.75 m $\times$ 0.30 m $\times$ 0.30 m laboratory tank in which the water level is kept constant (Figure 1). The vertical jet issues continuously from a nozzle with a nominal exit diameter D_0 of 5.4 mm located 55 mm above the undisturbed water level. The shape of the contraction inside the nozzle is especially designed to provide uniform flow at the exit. The jet velocity U_0 is 1.65 m/s. The corresponding values of the Reynolds number ($Re \equiv U_0 D_0/\nu$), the Froude number ($Fr \equiv U_0^2/gD_0$) and the Weber number ($We \equiv \rho U_0^2 D_0/\sigma$) are 12300, 52 and 202, respectively. Here ν is the liquid kinematic viscosity, σ the surface tension coefficient, and g the acceleration of gravity.

The disturbance was generated by rapidly injecting extra water from a pressurized reservoir by means of solenoid valves through four side holes with a diameter of 3.2 mm in the contraction section of the nozzle. The pressure in the reservoir P_{in} was varied from 20 to 60 psi to produce disturbances of different sizes on the jet. The valves were controlled by an IBM PC. A CCD camera (Pulnix TM-9701 with a Nikon lens) was used to capture the images of the air entrainment process. Lighting was provided by a computer-controlled strobe. By suitably adjusting the time delay between water injection, strobe lighting, and camera exposure, the image of the cavity at different stages can be captured and saved in the computer for further processing. In some experiments, a high-speed movie camera was also used, with the computer providing suitable timing between water injection and the beginning of the filming. The film was then digitized and stored in the computer.

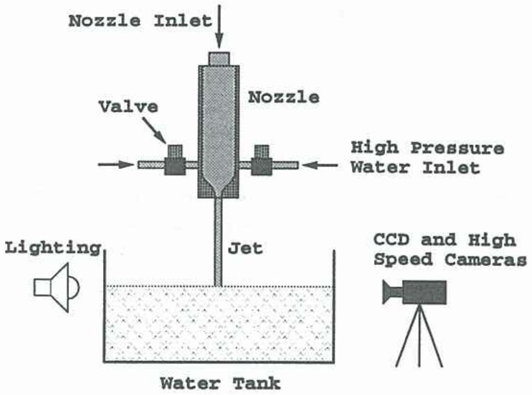

Figure 1: Experimental setup.

RESULTS

The injected extra water mass exiting from the nozzle causes the jet speed to be greater than that of the undisturbed jet and therefore catches up with the water that just left the nozzle. The consequence is the appearance of a bulge on the jet surface. Figure 2 shows the development of the bulge on the jet between the nozzle exit and the water surface. These images were taken with the CCD camera from different events by varying the time delay between water injection and strobe as explained before. Since the event is highly reproducible, they can however be considered as a sequence of images of a single event. The velocity measurements using a hydrolysis technique (Zhu et al., 1998) indicate that the bulge velocity is intermediate between the free-fall velocities of the undisturbed original jet and of the faster jet produced with the valves fully open. The size and phase speed of the bulge estimated from the images are also well supported by numerical simulations (Zhu et al., 1998).

The clarity of the reflection of the jet in the pool in Figure 2 indicates that, before the bulge hits the pool, the water surface is not disturbed and indeed no entrainment is observed. This observation contradicts the claim of Londong (see e.g. Biń, 1993) according to whom air entrainment occurs if $Fr > 10$ and $Re > 7000$, values that are exceeded in the present experiment without any entrainment. The large discrepancy between our results and Londong's observations is most likely due to a difference in the nozzle geometry. Different nozzle shapes affect the level of turbulence in the jet and therefore its roughness, with a consequent effect on the onset of the air entrainment. The present observation is however consistent with Lara's (1979) experiments.

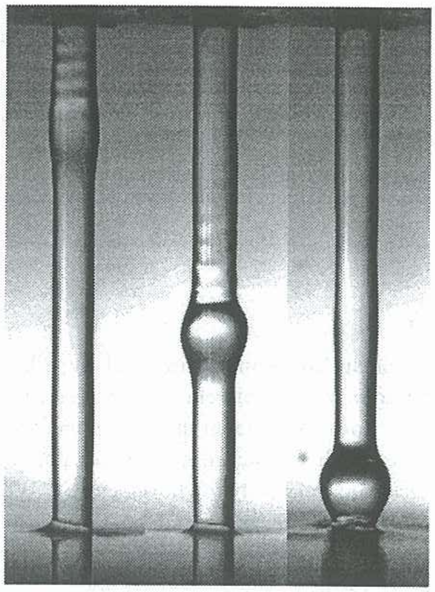

Figure 2: CCD images of the development of a jet disturbance between the nozzle and the receiving water surface. Gravity points downward. $P_{in} = 37$ psi. The normalized times tU_0/D_0 are, from left to right, 2.0, 5.6 and 8.1, respectively. Here t is calculated from the time when the bulge appears at the nozzle exit. The bulge diameter in the horizontal direction D_b is about 9.5 mm before it enters the water.

Figure 3 shows the development of the underwater air cavity induced by the disturbance on the jet. Also shown in the figure are the corresponding images generated from numerical simulations (left-hand side on each pair). The simulations are done based on the assumption that the flow is inviscid and axisymmetric with respect to the axis of the jet. Therefore, the flow can be approximated by an incompressible potential flow for which the velocity field is given by

$$\mathbf{u} = \nabla\phi, \qquad (1)$$

where $\nabla^2\phi = 0$ and ϕ is the velocity potential. The Bernoulli integral equation is used at the free surface. The boundary integral method is used for solving the velocity potential equation. Details of this method were given in Oguz et al. (1995).

Figure 3 indicates that there is a good agreement between the experiments and simulations. Both the experiments and simulations reveals that, when the bulge hits the water surface, it pushes the surface down and generates a cavity below the surface. The jet remains clearly visible inside the cavity. The cavity grows due to the transformation of the kinetic energy supplied by the jet and the bulge into gravitational potential energy. After the initial the impact of the bulge, the jet behind the bulge continues to advance and push the cavity front further down. This process can be seen in the second pair of the images.

(a)

(b)

(c)

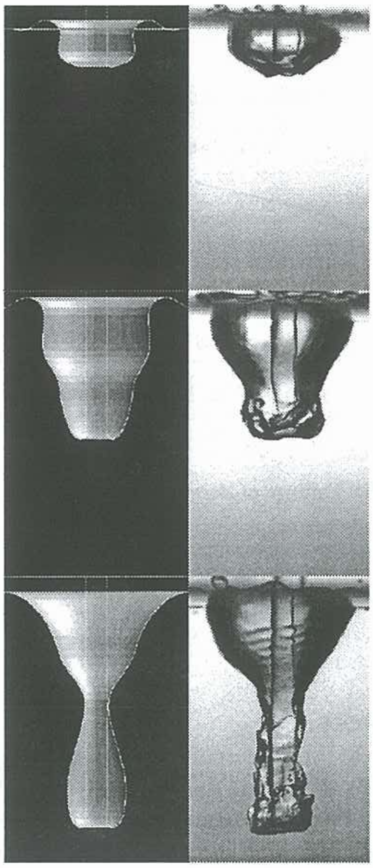

Figure 3: Development of an underwater air cavity induced by the jet disturbance - a comparison between experiments and numerical simulations. The dimensionless times tU_0/D_0, measured from the time when the bulge appears at the nozzle exit, are (a) 10.8 (b) 15.2 and (c) 20.3, respectively.

As the cavity depth grows, gravity effects become greater and greater, particularly near its bottom where the hydrostatically induced horizontal pressure gradient is largest. The bottom part of the cavity becomes thinner and, at a certain time, the side walls collapse onto the jet surface, entrapping a large toroidal air bubble. The entrapped air and the broken jet inside it continue to move downward before breaking up into smaller bubbles, while the remainder of the cavity above the pinch-off point is pushed back toward the surface.

The above observations (Figures 2 and 3) clearly indicate that the jet under the present conditions entrains air only when there are disturbances on the surface. However, it is still not clear if the disturbance is the only reason for causing air entrainment. In order to answer this question, a numerical experiment is carried out (Figure 4) in which the event is modeled by assuming that the jet is not involved in the process(treated as a hollow) and it is only the bulge that impacts the free surface. In this case, the bulge produces a cavity in which the bottom boundary moves down initially (Figure 4a). At $tU_0/D_0 \approx 12$ the bottom boundary begin to move upwards and then oscillates with respect to the water surface. The air cavity will never close up to entrap air. This numerical experiment indicates that the bulge itself cannot entrain air. It only works like a trigger. The air entrainment is caused by both the jet and the disturbance. A consideration of the energy balance supports this idea. For example, for the case of Figures 2 and 3, the kinetic energy of the bulge is much smaller than just the potential energy stored in the cavity (not including the kinetic energy of the surrounding water). This indicates that, although the cavity is initiated by the bulge, there is a mechanism at work by which energy is subtracted from the jet and used to form the cavity. This conclusion is substantiated by our second numerical experiment in which only part of the jet is involved in the process and the rest is treated as a hollow (i.e. the cylinder along the centreline in Figure 5). It can be seen that the process is approximately the same as the full jet case.

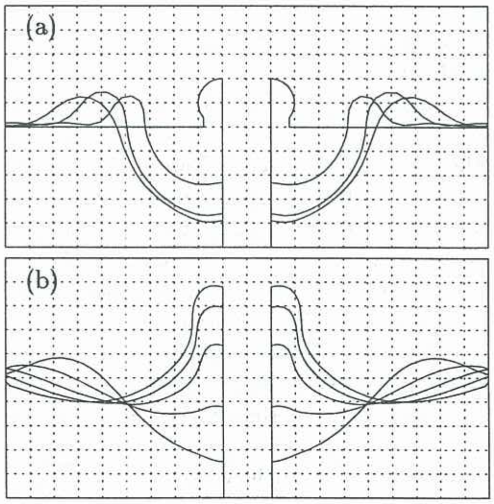

Figure 4: Numerical simulation: Development of air cavity induced by disturbance only. The non-dimensional times tU_0/D_0 are 0, 4, 8, 12 in (a) (from top to bottom) and 16, 20, 24, 28, 32 in (b) (from bottom to top), respectively.

From the images of the underwater cavity development, the volume of the entrapped air can be estimated. By applying an edge detection technique to the images, a two-dimensional projection of the cavity can be generated. We assume axial symmetry with a local radius given by the average of the two radii that can be measured from these projections. Upon subtracting the volume of the entrapped jet from the total volume of the detached part of the cavity we find the volume of the entrained air. The volume of entrapped air is also calculated for the simulations. The final shape of the cavity is used for calculation and the cavity is also assumed to be axisymmetric.

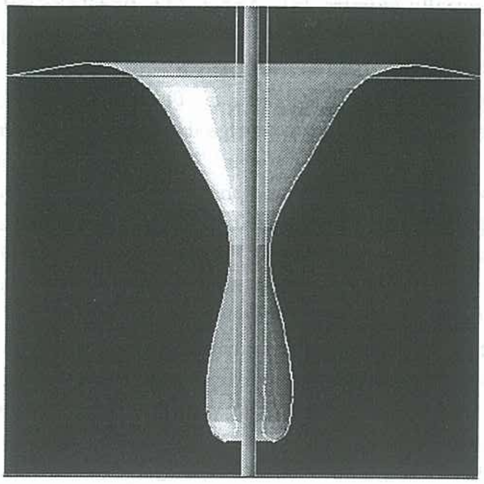

Figure 5: Numerical simulation: Final shape of the air cavity induced by disturbance and partial jet.

Figure 6 shows the entrapped air volume V_c as a function of the bulge size D_b. Both the measured and simulated data vary linearly with D_b. The experimental data indicate that the jet starts to entrain air only when the bulge size D_b/D_0 is larger than about 1.15. For smaller disturbances (e.g. $D_b/D_0 \leq 1.15$), there is no entrainment. However, the simulations over-predict the entrapped air by a considerable amount. This is mainly due to the fact that the simulations have been conducted by assuming in all cases that the entire jet impacts, i.e. that the entire jet energy is available for cavity formation. Another reason for the disagreement between experiment and calculation is the strong three-dimensional nature of the cavity evident in the experiment. Pinch-off does not occur at the same time all around the jet circumference. In its collapse, the hollow will continue to vent its air until the cavity is entirely closed. It is noteworthy that, in spite of the complexity of the effects neglected in the model, the difference with the data amounts to a nearly constant offset that can reasonably be estimated by calculating the air volume entrapped at zero bulge size, while the slopes of the two lines are very close.

CONCLUSION

We have studied the process by which a continuous jet falling onto the free surface of a liquid mass entraps air. We found that, without disturbances, the jet does not entrap air even when its Reynolds and Froude numbers exceed the thresholds reported by earlier investigators. In order to entrain air, it is necessary to introduce artificial disturbances. The jet disturbance thus generated interacts in a complex way with the jet itself and leads to the development of a relatively large air cavity the bottom part of which pinches off giving rise to air bubbles.

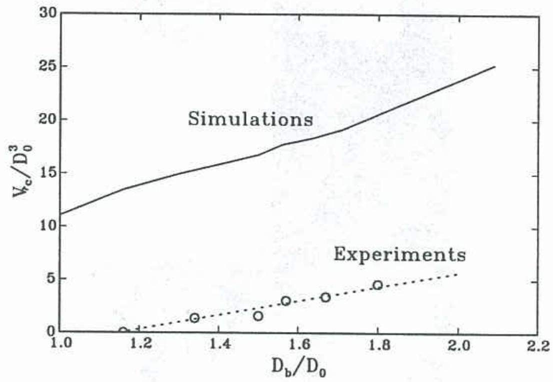

Figure 6: Volume of the entrapped air as a function of disturbance size.

ACKNOWLEDGMENT

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