13th Australasian Fluid Mechanics Conference
Monash University, Melbourne, Australia
13-18 December 1998

INDIVIDUAL AIR BUBBLE ENTRAINMENT AT A PLANAR PLUNGING JET WITH NEAR-INCEPTION FLOW CONDITIONS

P.D. CUMMINGS (1) and H. CHANSON (2)

(1) Kinhill Engineers, PO Box 1197, Brisbane QLD 4064, AUSTRALIA
(2) Department of Civil Engineering, The University of Queensland, Brisbane QLD 4072, AUSTRALIA

ABSTRACT

At a plunging liquid jet, air bubbles may be entrained if the impact velocity exceeds a critical velocity. New experiments were performed in a two-dimensional plunging jet to observe the flow conditions at inception. Two mechanisms of air entrainment were visualised : air bubble entrainment by elongated air cavity and by foam bubbles. After entrapment/entrainment, the breakage of entrained air bubbles depends critically upon the initial bubble size.

INTRODUCTION

At the impact of a water jet, air may be carried downwards. Examples of mechanical penetration of one phase into another include self aeration in free jets, high speed open channel flows, entrainment via surface vortices, drop impact, hydraulic jumps and breaking waves (e.g. BIN 1993, CHANSON 1997). Air entrainment by plunging jet is an industrially important process where air entrainment is desired but control (e.g. of bubble sizes) is necessary.

Past studies (e.g. ERVINE and ELSAWY 1975, LARA 1979) showed that air bubble entrainment takes place when the jet impact velocity V exceeds a characteristic value V_e which is primarily a function of fluid properties, jet length and jet core turbulence. For $V > V_e$, air entrainment is observed by an individual bubble entrainment process for V slightly larger than V_e, or by a ventilated cavity mechanism at larger jet impact velocities (CUMMINGS and CHANSON 1997a,b).

Most studies of air entrainment inception and individual air bubble entrainment were performed with circular jets. In the present paper, the writers present an experimental study of plunging jet entrainment with a simple geometry, specifically a supported two-dimensional plunging jet (fig. 1). The inception flow conditions and the individual bubble entrainment process were investigated using high-speed camera and video-camera, and the results are presented herein.

EXPERIMENTAL METHOD

The experiment consists of a fresh water planar jet (0.27-m wide, 0.012-m thick at nozzle) (fig. 1). The jet plunges into a 1.8 m deep, 0.3 m wide and 3.6 m long channel with glass walls. The jet angle with the horizontal was set at 89° to ensure that the jet remained attached to the support.

Discharges were measured with an orifice plate meter, and clear-water velocity and velocity fluctuations were recorded with a 3.3 mm Pitot tube. A Panasonic™ F15 CCD WV-F15HSE Cam-corder video camera was used to visualise air bubble entrainment below the plunge pool surface. The entrained bubbles were illuminated with a 500-W tungsten bulb lamp. The camera was equipped with a macro lens and used in strobe effect shutter mode : one frame taken every 20 ms with a 500 μs shutter speed. Scaling for the camera images was done by filming a spherical steel ball bearing of known diameter at various locations near the jet centre line. Bubbles outside of the ball bearing locations were out of focus and ignored. High-speed photographs were further taken with a 35 mm camera (35 μs shutter speed). Further information on the experiment is given by CUMMINGS (1996).

The surface tension was measured using glass capillary tubes (Ø = 1.2 to 3.2 mm) and found to be 0.055 N/m at 25 Celsius.

Ref.	V_e m/s	Tu %	d m	L_j m	Plung. jet
Present Study					
CU1	2.03	0.34	0.003	0.179	2-D jet.
CU2	1.79	0.50	0.0035	0.134	2-D jet.
CU3	1.14	1.19	0.008	0.034	2-D jet.
CU4	1.14	1.30	0.01	0.005	2-D jet.
CU5	1.20	1.08	0.009	0.017	2-D jet.
CU6	1.15	1.21	0.006	0.037	2-D jet.
CU7	1.17	1.36	0.0075	0.028	2-D jet.
ERVINE et al.					
ER1	3.6	0.003	--	--	Øjet.
ER2	2.5	0.01	--	--	Øjet.
ER3	1.0	0.03	--	--	Øjet.
ER4	0.8	0.08	--	--	Øjet.
McKEOGH					
MK1	0.85	5.0	0.0027	0.005	Øjet.
MK2	0.85	5.0	0.006	0.005	Øjet.
MK3	0.87	5.0	0.009	0.005	Øjet.
MK4	0.88	5.0	0.0145	0.005	Øjet.
MK5	2.78	1.0	0.0027	0.005	Øjet.
MK6	2.81	1.0	0.006	0.005	Øjet.
MK7	2.83	1.0	0.009	0.005	Øjet.
MK8	2.82	1.0	0.0145	0.005	Øjet.
EL-HAMMOUMI					
EH1	3.14	0.0028	0.0073	0.290	Øjet.
EH2	3.71	1.5E-4	0.012	0.290	Øjet.

Table 1: Inception of air entrainment (air and water experiments)
Note : d impact jet thickness, L_j jet length, V_e impact velocity

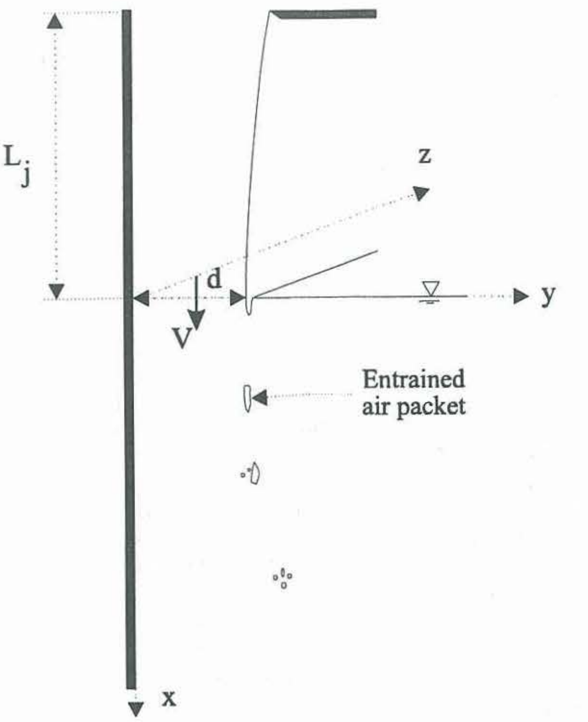

Fig. 1: Sketch of the experiment

INCEPTION OF AIR ENTRAINMENT

Experimental observations of air entrainment inception conditions are presented in figure 2 and table 1, where the onset velocity for air entrainment V_e is defined as the mean centreline jet velocity outside the developing boundary layer, at impact, Tu the jet turbulence intensity, d the jet thickness at impact and L_j the length of the free-falling jet. Tu was measured at the jet impact in the present experiments. McKEOGH (1978), ERVINE et al. (1980) and EL-HAMMOUMI (1994) recorded the jet turbulence at the nozzle. The writers, ERVINE and McKEOGH defined Tu in terms of the longitudinal velocity fluctuation while EL-HAMMOUMI recorded the turbulent velocity fluctuation in the direction normal to the jet flow.

It must be emphasised that the data depend critically upon the definition of air entrainment inception. The writers observed consistently that inception is not a precise condition. A jet may entrain one or a few bubbles only every few minutes. Hence the selection of the investigation period (e.g. 1 or 10 minutes) is critical. Further, after being entrained, some rising bubbles stay on the surface of the plunge pool as foam bubbles, drifting towards the jet entrainment point. Such bubbles may then become attached to the jet/pool intersection for a period of time, before being re-entrained. Sometimes the re-entrainment caused by the surface foam bubbles consists of an air packet that is considerably larger than the original bubble and the "primary" entrainment may be followed by numerous "secondary" events until all of the bubbles have been cleared from the system.

In the study, the writers defined "inception" as a "primary" entrainment event which occurs within an interval of about 5 minutes, in the absence of bubbles in the plunge pool.

Analysis

Despite different definitions of "inception" and of Tu, the data (fig. 2) indicate a decreasing inception velocity with increasing turbulence level. The trend is consistent with circular jet data. At the limits, V_e tends to about 3.5 m/s for very-low turbulence jets (Tu < 1 E-5) and to 0.8 m/s for turbulent jets (Tu > 0.1). Altogether the inception velocity of air-water plunging jets may be estimated as :

$$V_e = 0.8 + 2.7 * \exp(-100*Tu) \qquad (1)$$

where V_e is in m/s.

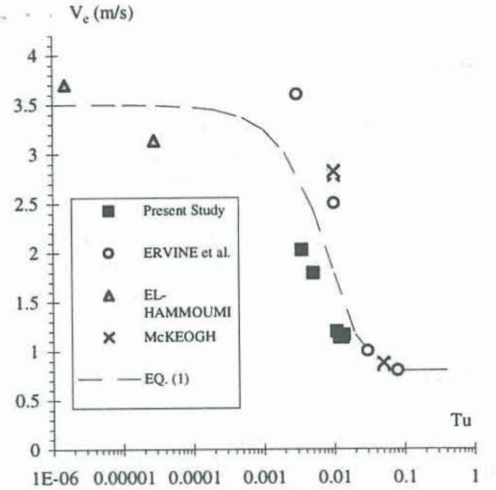

Fig. 2: Inception velocity of air entrainment

INDIVIDUAL AIR BUBBLE ENTRAINMENT AT NEAR-INCEPTION FLOW CONDITIONS

At low jet velocities and $V \geq V_e$, air is entrained in the form of individual air bubbles and new photographic evidence highlights two main entrapment process : (a) entrainment via an elongated air cavity and (b) entrainment via surface foam bubbles.

Air entrainment by elongated air cavity is illustrated in figure 3 which is a sketch made from consecutive frames of video-camera film. Note that the scale applies to the four lowest figures, figures 3.1 and 3.2 being scaled upwards for a better understanding.

In figure 3, an air pocket extends downwards from the jet-plunge pool intersection (fig. 3.1 & 3.2). The end of the cavity breaks off to form several individual bubbles (fig. 3.4 to 3.6). The analysis of video-camera pictures indicates that the air cavities are typically 7 to 18 mm long and the transverse dimension is about 1.0 to 4.5 mm. Generally elongated air cavities are observed to occur under areas of high free-surface "roughness" on the impinging jet.

Figure 4 illustrates air bubble entrainment by surface foam bubble being trapped at the jet-plunge pool intersection. The trapped bubbles perturb the jet interface sufficiently for bubbles to be entrained. Note that tap water was used and small quantities of surfactants were present although their quantity was not measured.

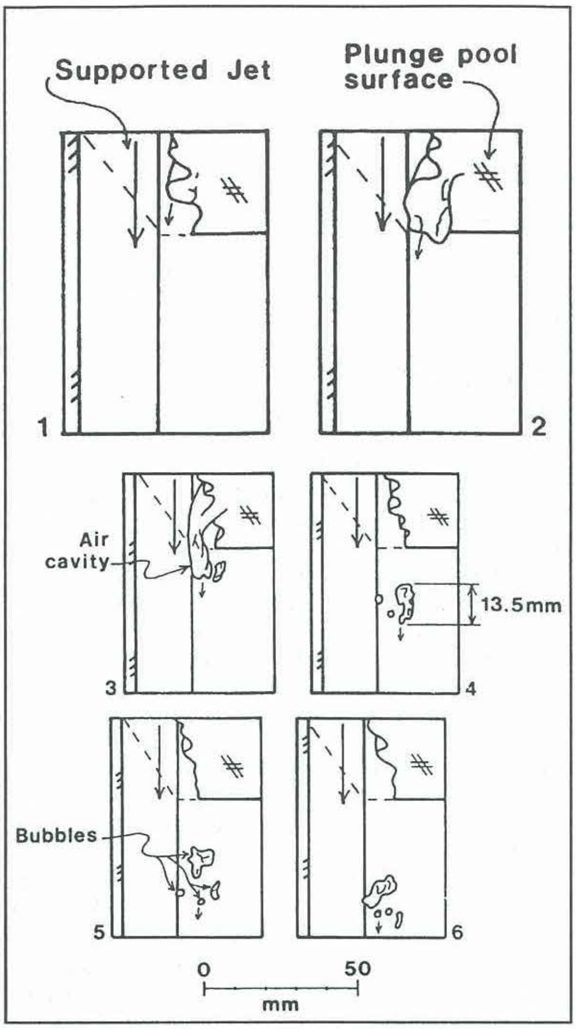

Fig. 3: Elongated air cavity formation and entrainment of bubbles. Flow direction from top to bottom : V = 1.20 m/s, Tu = 1.08 %, d = 8.0 mm, L_j = 34 mm. Video shutter speed : 1.0 ms, frame interval : 20 ms

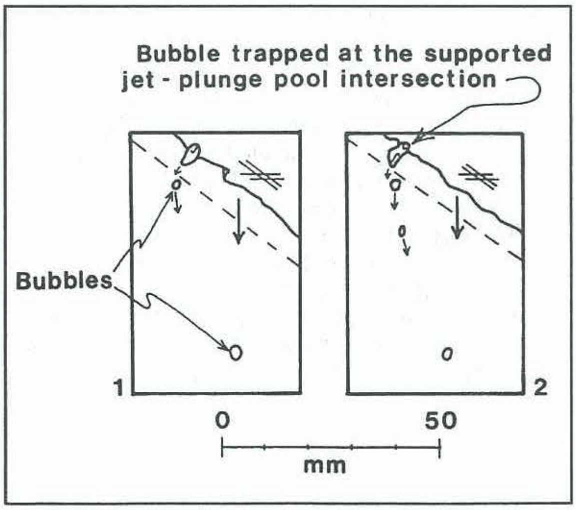

Fig. 4: Air bubble entrainment caused a trapped surface bubble. Flow direction from top to bottom :V = 1.20 m/s, Tu = 1.08%, d = 8.0 mm, L_j = 34 mm. Video shutter speed : 1.0 ms, frame interval : 20 ms.

Other forms of air bubble entrainment may be sometimes observed. Surface foam can be entrained, air contained within the jet body can be carried under the plunge pool surface, and small bubbles are entrained possibly via small surface cavities.

BUBBLE BREAKAGE

After entrainment/entrapment at the jet-pool intersection, air bubbles are carried away in a developing shear layer and bubble breakage may occur. Several researchers proposed to use a criteria for breakage based upon a critical Weber number (HINZE 1955, SEVIK and PARK 1973), but such a formulation assumes an uniform turbulent shear stress distribution which is untrue in a mixing layer.

New observations of bubble breakage were recorded with near inception flow conditions : i.e., from {V = 1.17 m/s, Tu = 1.38%, d = 10.0 mm and L_j = 5 mm} to {V = 2.03 m/s, Tu = 0.35%, d = 3.0 mm, L_j = 179 mm}. Most bubble breakage events were observed between x = 50 and 100 mm, for which the shear layer width (measured between 0.1*V and 0.9*V) was about 14 to 24 mm.

For about 200 single-bubble breakages, the number and size of "daughter" particles were recorded (fig. 5 and 6). The writers defined a "breakage" as an event that occurred between two successive video frames (i.e. 20 ms period) and, for each experiment, the apparent bubble diameter *D* is the average of the measured bubble major- and minor-axes lengths.

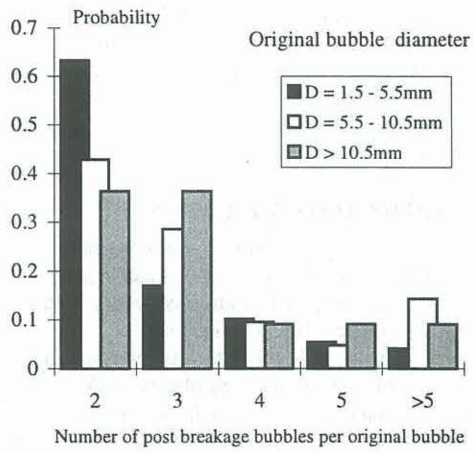

Fig. 5: Single bubble breakage : number of breakage products per original bubble

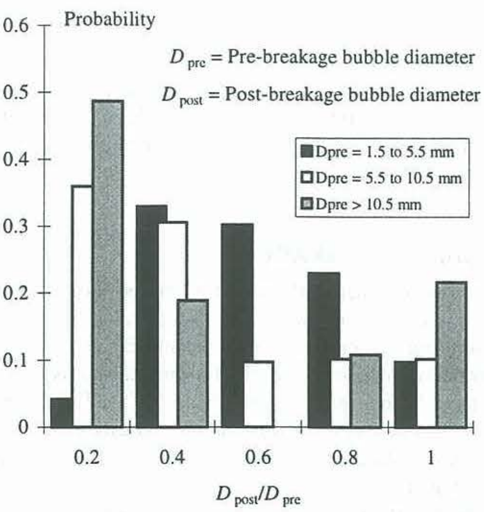

Fig. 6: Single bubble breakage : dimensionless post-breakage bubble size

Figure 5 shows the number of post-breakage bubbles per original bubble ("parent-bubble") for three ranges of parent bubble diameters D. The results illustrate that most smaller bubbles break into two particles whereas the breakage of larger bubbles ($D > 10.5$ mm) tend to give in average 2.7 daughter bubbles. Such a result might result from different modes of breakage with different "parent-bubble" size.

Figure 6 presents experimental observations of "daughter" bubble sizes, presented as the ratio of post- to pre-breakage bubble size. Each histogram column represents the probability of the ratio D_{post}/D_{pre} in a 0.2 interval : e.g., the column 0.8 indicate the probability of $0.8 < D_{post}/D_{pre} \leq 1$. For small bubbles ($D_{pre} < 5.5$ mm), the daughter bubbles are in average 2.3 times smaller than the parent-bubble while, with the largest bubbles ($D_{pre} > 10.5$ mm), the ratio D_{post}/D_{pre} is predominantly less than 0.2.

SUMMARY AND CONCLUSION

The inception of air bubble entrainment by a vertical supported planar plunging water jet has been investigated. Inception conditions depend critically upon the jet turbulence (Eq. (1), Fig. 2).

At near-inception flow conditions, two new mechanisms of air bubble entrainment are observed. An elongated air cavity mechanism is observed, associated with areas of jet free-surface irregularities. If the jet free-surface is exceptionally smooth, this mechanism may not be present until a higher jet speed is attained. Air entrainment was also observed to be caused by the presence of foam bubbles at the jet-plunge pool intersection.

Bubble breakage mechanisms were studies below the jet impingement point. Data indicate that the bubble breakage process is a function of the bubble size. Small bubbles ($D < 5.5$ mm) are deformed into a kidney shape prior to breaking, splitting into two particles of nearly equal size. Larger bubbles were observed to stretch into elongated shapes prior to breakage.

The present study provides a new understanding of the low jet velocity entrainment process by plunging jet. However the extension of the study to large jet velocity is necessary and new experimental techniques will be required.

ACKNOWLEDGMENTS

The authors wish to thank particularly Professor C.J. APELT, University of Queensland who supported this project since its beginning. They acknowledge the financial support of the Australian Research Council (Ref. No. A89331591).

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