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ENTRAINMENT, DISPERSION AND DIFFUSION OF AIR BUBBLES BY PLUNGING WATER JET

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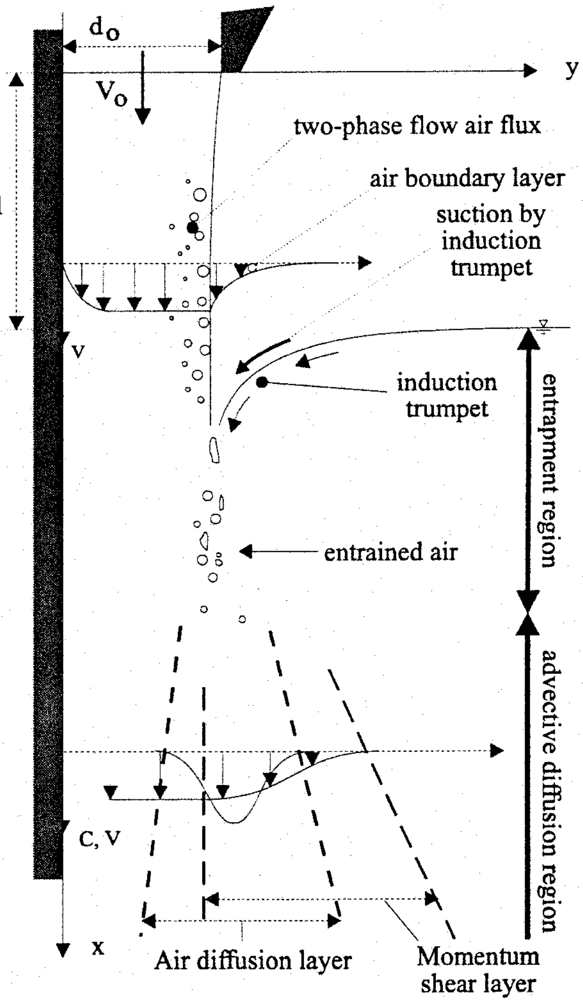
Introduction

A plunging jet flow is defined as the impingement of a rapid flow into a slower body of liquid : e.g., pool of liquid at rest, a tranquil channel flow (fig. 1). At the intersection of the impinging flow with the receiving body of water, free-surface instabilities develop and air bubble entrainment is observed. Practical applications include the impact of waterfalls, mixing devices in chemical plants, drop structures in rivers. A related case is the air entrainment by a plunging solid surface (BURLEY and JOLLY 1984) and air entrainment by plunging breaking waves (e.g. COLES 1967, CHANSON and LEE 1997).

Numerous studies were conducted with thin circular jets (BIN 1993). However few studies investigated two-dimensional plunging jets (e.g. GOLDRING et al. 1980, SENE 1988, CUMMINGS and CHANSON 1997a,b).

The present paper describe new experiments performed with a supported plunging jet (fig. 1). The measurements were performed in the developing flow region : i.e., with a developing air diffusion layer and developing shear flow. The results provide new information on the air bubble diffusion process and the characteristic sizes of entrained bubbles for impact velocities ranging from 2 to 8 m/s.

Fig. 1 (Right) - Air entrainment at a two-dimensional plunging jet



Experimental facility

Description

New experiments were conducted in the plunging jet channel used by CUMMINGS and CHANSON (1997b). The experimental apparatus consists of a fresh-water planar jet issuing from a 0.269-m by 0.012-m slot nozzle and plunging into a 0.3-m wide 1.8-m deep glass-wall pool. The jet support is 0.35-m long and its angle with the horizontal is 89 degrees, The water supply (Brisbane tap water) comes from a constant-head tank. The discharge was measured with orifice meters (error less than 1%). The displacement of the probes in the direction normal to the jet support and along the jet direction was controlled by two fine adjustment travelling mechanisms, and the positions were measured with two Lucas Schaevitz Magnarules Plus™. The error in the longitudinal and normal positions of the probes was less than 0.1 mm in each direction.

Air-water flow properties were recorded using double-tip conductivity probes. The two tips, aligned in the direction of the flow, are identical with an internal Platinum electrode (∅ = 25 μm) and an external annular electrode (∅ = 200 μm). Both tips were excited by a specially-designed electronic system and the signals were scanned at 40 kHz per channel.

Additional measurements were performed using high speed photographs with flash speeds of 33 to 67 μs (e.g. CHANSON 1997, pages 12, 19, 46, 55). Full details of the apparatus and the complete set of data are presented

Aspects of data processing

Although the data processing of conductivity probe signals could be ideally very simple, difficulties were encountered as a result of probe contamination. A single threshold value processing technique was used. This technique might not be the most accurate depending upon the type of bubble collision with the probe tip (e.g. piercing, glancing, sliding collision types). However it was found to be most reliable when dealing with both high-air content and low-air-content regions of plunging jet flow. For all the experiments, the threshold for the discrimination between air and water was set at the 50% level between the air and water voltages.

Inflow conditions

Several authors showed that air entrainment by plunging jet is affected critically by the characteristics of the impinging liquid jet. During the present study, the turbulent boundary layer developing along the support was always thin and could not be detected with the instrumentation in most cases. The result was confirmed by boundary layer calculations, assuming a smooth turbulent boundary layer in absence of pressure gradient. That is, the inflow was partially-developed.

The properties of the impinging jet and of its free-stream region were studied in details. The turbulence characteristics of the 'potential core' were recorded using a conical hot-film probe. High levels of turbulence in the impinging free-stream were observed : Tu_1 = 1.7 to 3 % measured at $y/d_1 = 2/3$. These results are consistent with earlier observations recorded with a Pitot tube (CHANSON 1995, CUMMINGS and CHANSON 1997b).

Air concentration measurements near the free-surface of the free-falling jets indicate a substantial aeration at the impinging jet free-surface. The dimensionless quantity of entrained air $(q_{air}/q_w)_1$ ranged from 0.08 to 0.24 depending upon the jet length and impact velocity.

Air-water flow characteristics

Presentation

Air entrainment by plunging jet is a combination of different processes by which air packets/bubbles are carried away within a developing shear flow (fig. 1). New experimental observations indicate that the developing air-water shear region consists of an *entrapment region* in which the flow properties are strongly affected by the entrainment/entrapment processes followed by an *advective diffusion region* in which the air bubble dispersion may be predicted by a simple advective diffusion theory.

For the experiments, the entrapment region length was observed to be about $5*d_1$ where d_1 is the jet impact thickness (fig. 1).

Void fraction and mean velocity distributions

In the advective diffusion region, the air concentration (i.e. void fraction) distributions follow closely a solution of the diffusion equation (fig. 2) :

$$C = \frac{\frac{q_{air}}{q_w}}{\sqrt{4 * \pi * D^\# * \frac{x - x_1}{Y_{CM}}}} * \left(\exp\left(- \frac{\left(\frac{y}{Y_{CM}} - 1\right)^2}{4 * D^\# * \frac{x - x_1}{Y_{CM}}} \right) + \exp\left(- \frac{\left(\frac{y}{Y_{CM}} + 1\right)^2}{4 * D^\# * \frac{x - x_1}{Y_{CM}}} \right) \right) \quad (1)$$

where q_{air} is the volume air flow rate per unit width, $D^\# = D_t/(V_1 * Y_{CM})$, D_t is the turbulent diffusivity, x_1 is the free-falling jet length and Y_{CM} is the distance from the support where C is maximum (CHANSON 1997). The main characteristics of the diffusion process become Y_{CM}, D_t and q_{air}, the former being best correlated by :

$$\frac{Y_{CM}}{d_1} = 0.0639 * \frac{x - x_1}{d_1} + 1.1896 \qquad \text{for } (x - x_1)/d_1 \le 21 \text{ and } 2 \le V_1 \le 8 \text{ m/s} \quad (2)$$

and observed values of D_t and q_{air} being presented in table 1.

Interestingly the distributions of mean air-water velocity have the same shape as in monophase flow :

$$\frac{V}{V_1} = \frac{1}{2} * \left(1 + \operatorname{erf}\left(\frac{1}{2} * \sqrt{\frac{V_1 * d_1}{\nu_T}} * \frac{y - y_{50}}{\sqrt{d_1 * (x - x_1)}} \right) \right) \quad (3)$$

where y_{50} is the location where $V = V_1/2$, ν_T is the eddy vicosity and erf is the Gaussian error function.

Such a similarity of shape of the velocity distributions in monophase and air-water flows was observed independently by ROIG (1993) and CUMMINGS and CHANSON (1997b), and it was confirmed by the new series of experiments. The data indicate that the symmetry line of the shear layer y_{50} is shifted outwards from the jet centreline :

$$\frac{y_{50}}{d_1} = 0.09386 * \frac{x - x_1}{d_1} + 1.4979 \qquad \text{Data: Present study} \quad (4)$$

with a normalised coefficient of correlation of 0.945 while, for monophase flows, the following relationship holds:

$$\frac{y_{50}}{d_1} = 0.05 * \frac{x - x_1}{d_1} + 1.005 \qquad \text{Data: WYGNANSKI and FIEDLER (1970)} \quad (5)$$

The results are consistent with the earlier observations of CUMMINGS and CHANSON (1997b).
The eddy viscosity was deduced from the best data fit (table 1). The results indicate consistently that the rate of expansion of air-water shear layers is greater than that of monophase shear layers. Interestingly the same trend was observed with low-velocity mixing layers (ROIG 1993).

Fig. 2 - Distributions of air concentration, mean velocity and bubble frequency in a 2D supported plunging jet - $V_1 = 8$ m/s, $x_1 = 0.1$ m, $d_1 = 0.012$ m

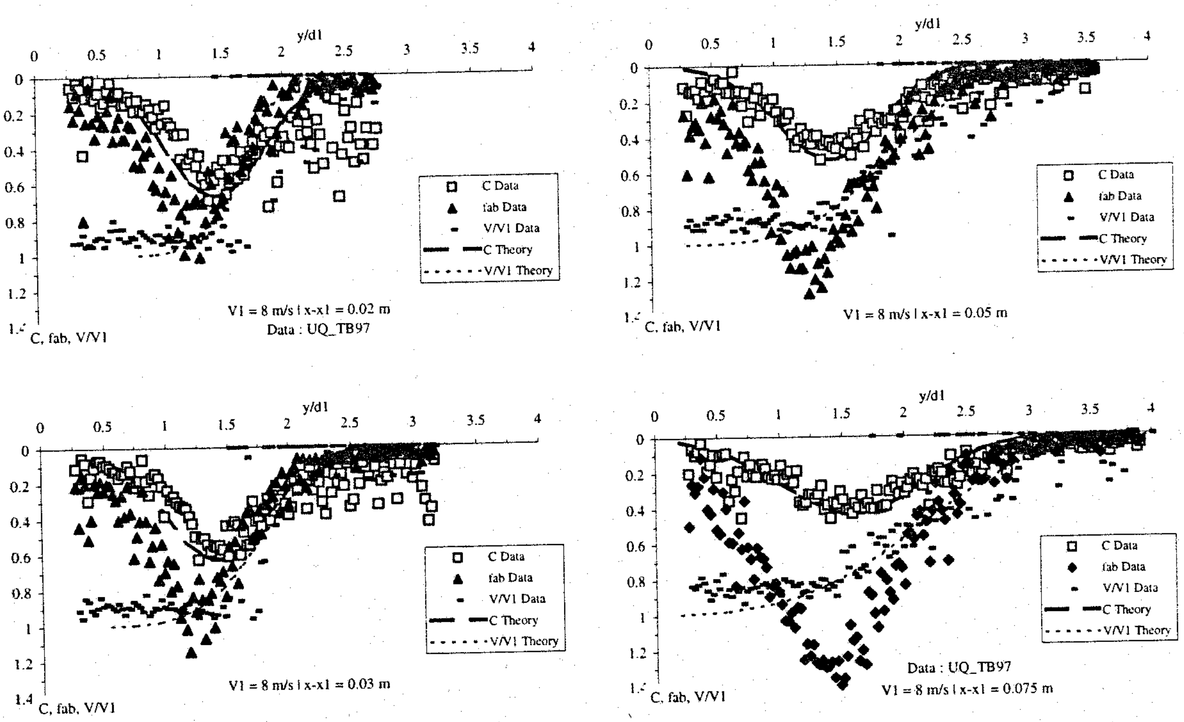


Table 1 - Air bubble diffusivity, eddy viscosity and upper limit of maximum bubble frequency in the developing shear region of plunging water jets

Ref.	V_1 (m/s)	d_1(m)	$\frac{q_{air}}{q_w}$	$\frac{D_t}{V_1 * d_1}$	$\frac{\nu_T}{V_1 * d_1}$	$\frac{F_M * d_1}{V_1}$ (b)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
CUMMINGS (1996) (a)	2.39	0.010	0.061	3.92E-2	1.09E-2	--
	6.14	0.0117	0.538	3.72E-2	2.69E-2	--
Present study	2.0	0.0090	--	--	5.40E-2	0.132
	3.0	0.0110	0.135	1.91E-2	4.82E-2	0.506
	4.0	0.0116	0.274	2.74E-2	3.33E-2	0.725
	5.0	0.0119	0.293	4.14E-2	4.12E-2	0.928
	6.0	0.0120	0.372	5.31E-2	3.37E-2	1.13
	7.0	0.0121	0.364	2.64E-2	2.20E-2	1.33
	8.0	0.0121	0.450	3.26E-2	1.93E-2	1.41

Notes: (a): analysis by CHANSON (1997); (b): upper limit; (--): not available.

Air bubble frequency and bubble sizes

Some information on the air-water flow structure derives from the behaviour of the air bubble frequency. Transverse distributions of air bubble frequency exhibit a characteristic triangular shape with a maximum at a distance Y_{FM} from the support (fig. 2).

The transverse profile may also be presented as bubble frequency versus void fraction (fig. 3). Two characteristic shapes are observed. In the *entrapment region*, the dimensionless air bubble frequency distributions are best fitted by :

$$f_{ab} = \frac{F_{ab} * d_1}{V_1} \propto C^{0.8} \qquad \text{for } (x - x_1)/(0.5*V_1^2/g) \le 0.04 \quad (6a)$$

while the data are correlated in the *advective diffusion region* by :

$$f_{ab} = \frac{F_{ab} * d_1}{V_1} \propto C^{1.5} \qquad \text{advective diffusion region} \quad (6b)$$

At each cross-section, a maximum bubble frequency $F_M(x)$ is observed at $y = Y_{FM}$ which is best correlated by :

$$\frac{Y_{FM}}{d_1} = 0.0219 * \frac{x - x_1}{d_1} + 1.558 \qquad (7)$$

The longitudinal variations of maximum bubble frequency F_M indicate consistently an increasing maximum F_M immediately downstream of the impingement point, an upper limit (table 1, column 7), followed by an exponential decay (fig. 4). This trend suggests that some entrained bubbles are broken up into smaller bubbles immediately downstream of the entrapment point ($x = x_1$). The result is consistent with the observations of CUMMINGS and CHANSON (1997b).

Discussion

At each measurement point {x,y} in the shear layer, chord length data exhibit a wide range of sizes, from less than 0.1 mm to more than 40 mm. For any bubble size shape, bubble size distribution and chord length distribution, the mean chord length size (Number Mean Size) is related to the air content, velocity and bubble frequency by :

$$(ch_{ab})_{NMS} = \frac{C * V}{F_{ab}} \qquad (8)$$

According to equation (8), the mean chord length size is of the order of magnitude of 1 to 2 mm across the shear layers. Combining equations (6) and (8), the two-dimensional distributions of bubble frequency imply the entrainment of large-size air packets which are subsequently broken into small-size bubbles in the entrapment region and carried away by turbulent advective diffusion in the advective diffusion region.

Fig. 3 - Air bubble frequency distributions in the developing shear layer (V_1 = 6.14 m/s, d_1 = 0.012 m, x_1 = 0.09 m)

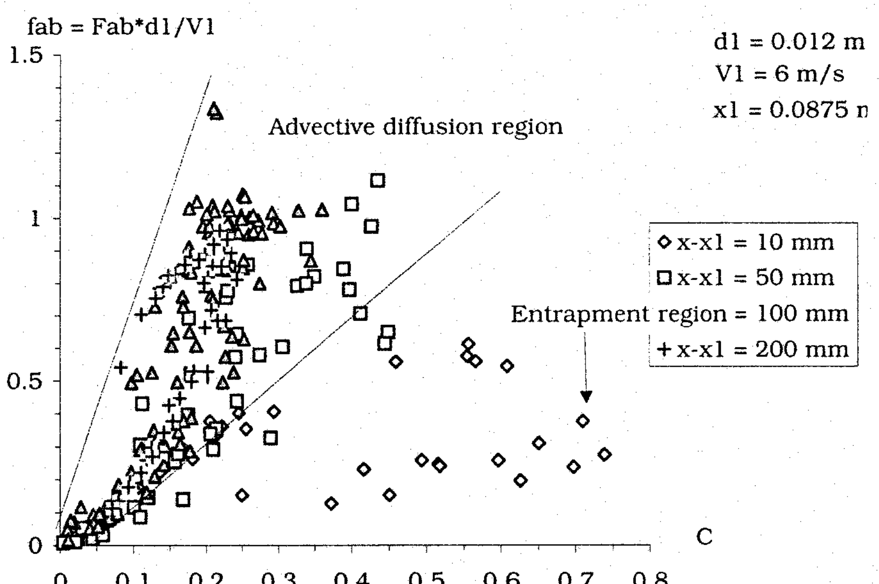
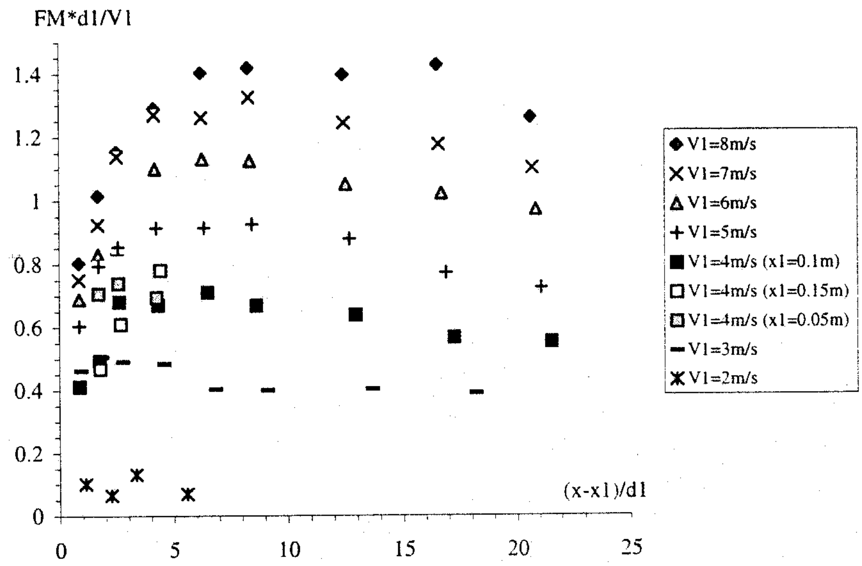


Fig. 4 - Longitudinal distribution of the dimensionless maximum air bubble frequency



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Summary and conclusion

The developing flow region of a two-dimensional plunging jet comprises a very-near flow field (entrapment region) in which the flow characteristics are strongly affected by the entrapment/entrainment conditions and a turbulent diffusion region. The present study has investigated specifically the air-water flow properties in the turbulent diffusion region for inflow velocities ranging from 2 to 8 m/s.

In the developing shear flow, the distributions of air concentration follow closely analytical solutions of the advective diffusion equation. Such a result suggests that the air bubble entrainment in air-water shear flows is predominantly a turbulent advective dispersion.

Distributions of mean air-water velocity exhibit the same shape as those observed in monophase flows. But the quantitative characteristics of the shear layers are significantly affected by the interactions between the entrained air bubbles and the turbulence. For all flow conditions, the momentum shear layer and the air bubble diffusion layer do not coincide.

Air bubble frequency distributions tend to have a triangular shape at each cross-section with a maximum in the shear layer. Interestingly the location of maximum bubble frequency does not coincide with the shear layer centreline nor with the air diffusion layer centreline. At a given cross-section the following relationship holds:

$$d_1 < Y_{FM} < Y_{CM} < y_{50} \tag{9}$$

With inflow velocities ranging from 2 to 8 m/s, the overall results suggest strong interactions between the entrained air bubbles and the momentum transfer process in the mixing layer. More could be gained by conducting both microscopic and macroscopic investigations: i.e., at the length scale level of the bubble size to comprehend the bubble break-up process, and at the length scale level of the large vortical structures responsible for the advective diffusion process.

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