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DEVELOPING AIR-WATER SHEAR LAYERS OF TWO-DIMENSIONAL WATER JETS DISCHARGING INTO AIR

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ABSTRACT

The paper presents new experiments performed in the developing flow region of two-dimensional water jets discharging into air. The results indicate that the distributions of void fraction follow closely an analytical solution of the diffusion equation, and that the transfer of momentum between the water jet and the surrounding air is negligible for $x/d_o < 20$. An analogy with self-aerated open channel flows is further developed. The distributions of air bubble frequency have the same shape for both flow situations suggesting some similarity in the air-water flow structure.

Keywords : water jets, air entrainment, developing flow, experimental measurements, analogy with self-aerated flows.

INTRODUCTION

Turbulent water jets discharging into the atmosphere are often characterised by a substantial amount of air entrainment. Applications include water jets at bottom outlets to dissipate energy, jet flows downstream of a spillway ski jump, mixing devices in chemical plants, spray devices, fire-fighting equipment and jet cutting equipment (e.g. coal mining). A related case is the ventilated cavity flow, observed downstream of blunt bodies, on the extrados of foils and turbine blades, at spillway aeration devices, behind a body impacting into a pool.

With a turbulent water jet, aeration occurs along the air-water jet interfaces. The effects can be detrimental (e.g. loss of jet momentum) or beneficial (e.g. mixing enhancement). In any case, knowledge of the air entrainment mechanisms is essential for an optimum design.

Some experimental results are available on the free-surface aeration of circular water jets (e.g. HERAUD 1966, ERVINE and FALVEY 1987, RUFF et al. 1989, TSENG et al. 1992) but there is little information on the free-surface aeration of two-dimensional water jets (see review in CHANSON 1997a). This paper describes new experiments performed with two-dimensional water jets discharging into air. The study is focused on the air-water flow properties of the developing flow.

EXPERIMENTAL APPARATUS

Experimental channels

Three experimental configurations were used (Fig. 1, Table 1). Experiment No. 1 is basically a water wall jet. Experiment No. 2 is an air-water free-shear layer at an abrupt drop. The third experiment is a vertical free-falling jet issuing from a slot nozzle and discharging downwards.

Discharges were measured with a Venturi-type device (i.e. Dall™ tube) in experiments No. 1 and No. 2, and with orifice meters in experiment No. 3. The error on the discharge measurement was less than 2%.

For experiments No. 1 and 2, the vertical probe translation was controlled by a fine adjustment travelling mechanism connected to a Mitutoyo™ digimatic scale unit. The error on the vertical position of the probe was less than 0.025 mm and the accuracy on the longitudinal position of the probe was less than 1 cm. In experiment No. 3, the displacements of the probe in the direction normal to and along the jet support were controlled by two fine adjustment travelling mechanisms (made in-house) and the positions were measured with two Lucas Schaevitz Magnarules Plus.

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The error in the longitudinal and normal positions of the probes was less than 0.1 mm in each direction.

Instrumentation

The air-water flow properties were recorded using conductivity probes made at the University of Queensland (CHANSON 1995a, CUMMINGS and CHANSON 1997).

A single-tip conductivity probe (inner electrode ∅ = 0.35 mm, outer electrode ∅ = 1.42 mm) was used to perform air concentration measurements in experiments No. 1 and 2. A two-tip conductivity probe was used to record simultaneously air concentration, air-water velocity and bubble frequency in experiment No. 3. Each tip was identical with an internal concentric electrode (∅ = 25 μm) and a 8-mm tip spacing. Both conductivity probes were excited by an electronic system designed with a response time less than 10 μs. The measurements were recorded with a scan rate ranging from 10 to 20 kHz per channel.

In addition clear water jet velocities were measured with a Pitot tube (Ø = 3.3 mm).

AIR-WATER FLOW CHARACTERISTICS

In the water jets, the air concentration distributions follow closely a solution of the diffusion equation :

$$C = \frac{1}{2} * \left(1 - \mathrm{erf}\left(\frac{y}{2 * \sqrt{\frac{D_t}{V_o} * x}}\right)\right) \qquad (1)$$

where x is the distance in the flow direction, y is the distance normal to the flow, V_o is the nozzle velocity, D_t is the turbulent diffusivity, assumed independent of the transverse direction y (CHANSON 1996) and the function erf is defined as :

$$\mathrm{erf}(u) = \frac{2}{\sqrt{\pi}} * \int_0^u \exp(-t^2) * dt \qquad (2)$$

Equation (1) was developed and validated for a two-dimensional free-shear layer. Note that it may be applied to all three investigated flow configurations (fig. 1), suggesting that the gradual diffusion/advection of air bubbles is nearly independent of the flow situations. The result (eq. (1)) may be extended to the developing flow region of a two-dimensional water jet discharging into the atmosphere but it is not valid when the jet core become aerated.

Air-water velocity and bubble frequency distributions were recorded in experiment No. 3 (fig. 2). In the near-flow field (i.e. $x/d_o < 20$), the transfer of momentum from the water jet to the air is small and the velocity distributions are basically not affected by the advective diffusion of air bubbles. The velocity distribution is nearly constant across the developing air-water layer. For a free-falling jet (experiment No. 3), it yields :

$$V = V_o * \sqrt{1 + \frac{2*g*x}{V_o^2}} \qquad \text{for } C < 0.90 \text{ and } x/d_o < 17 \quad (3)$$

where d_o is the jet nozzle thickness and g is the gravity acceleration.

The variation of air bubble frequency gives some information on the air-water flow structure. Experimental data show a maximum bubble frequency for 50% air content. At a given cross-section (i.e. x constant), the relationship bubble frequency-void fraction follows closely a parabolic shape (fig. 3) :

$$f = \frac{F}{F_M} = 1 - 4 * (C - 0.5)^2 \qquad (4)$$

where F is the air bubble frequency and F_M is the maximum frequency which is best correlated by :

$$F_M = 1.242 * \frac{\sqrt{x*d_o}}{V_o} \qquad \text{for } \rho_w * \frac{V_o*x}{\mu_w} > 1.5\text{E}+5 \quad (5)$$

where ρ_w and μ_w are the water density and dynamic viscosity respectively.

Bubble chord length distributions are presented in figure 4. The data (fig. 4) are cumulative bubble chord length distributions for 0 < C < 0.90 at various distance x from the nozzle. The histogram columns represent each the probability of a bubble chord length in 0.5-mm intervals: e.g., the probability of a chord length from 2.0 to 2.5 mm is represented by the column labelled 2.5. The last column (i.e. 100-mm) indicates the probability of bubble chord lengths larger than 100-mm.

The results (fig. 4) show the broad spectrum of bubble chord lengths : i.e., from less than 0.5-mm to larger than 100-mm. The distributions are skewed with a preponderance of small bubble sizes relative to the mean. The probability of bubble chord lengths is the largest for bubble sizes between 0 and 2.0 mm. Close to the jet nozzle (fig. 4A), most entrained air bubbles have small sizes. Further downstream the distribution of chord length is redistributed toward larger sizes (fig. 4B).

INTERFACIAL AERATION : SIMILARITY WITH SELF-AERATED FLOWS

Presentation

There is some similarity between air entrainment in high-velocity water jets and in supercritical open channel flows (fig. 5). Both flow configurations are high-speed turbulent flows with interfacial aeration rather than local aeration as in hydraulic jumps and plunging jet flows. In water jets and open channel flows, the air bubbles are gradually diffused/dispersed within the mean flow and the distributions of air concentrations have the same shape (fig. 2 and 6). The channel invert is analog to the jet centreline and the solution of the diffusion equation yields at equilibrium :

$$C = 1 - \tanh^2\left(K' - \frac{y'}{2 * D'}\right) \qquad \text{Open channel flow (6)}$$

where $K' = \tanh^{-1}(\sqrt{0.1}) + 0.5/D'$, $D' = D_t/((u_r)_{Hyd}*\cos\alpha*Y_{90})$, $(u_r)_{Hyd}$ is the rise velocity in hydrostatic pressure gradient, α is the invert slope, $y' = y/Y_{90}$, y is the distance normal to the invert and $y = Y_{90}$

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when C = 0.9 (CHANSON 1997a). The dimensionless turbulent diffusivity D' is a function of the mean air content only.

Further identical bubble frequency distributions (i.e. eq. (4)) are observed in both free-jets and fully-developed supercritical flows, suggesting that the air-water flow structure might be similar (CHANSON 1997b).

Discussion

A comparison of the turbulent diffusivity D_t, used in equations (1) and (6), shows that $D_t/(V_o*d_o)$ ranges from 1.5E-3 to 1.7E-2 for the present study (water jets) while $D_t/(V_{90}*Y_{90})$ is between 2.7E-3 and 1.6E-2 for the data of STRAUB and ANDERSON (1958) (open channel flow, fig. 6). The results are of the same order of magnitude, suggesting again some similarity in the advection/diffusion process.

The major differences between the two flow configurations are the shear layer characteristics. Self-aerated open channel flows are fully-developed shear flows while the developing air-water region of water jets is a free shear layer. In addition gravity effects (i.e. buoyancy) are significant in open channel flows.

CONCLUSION

The paper presents new experiments performed in the developing flow region of two-dimensional water jets discharging into air. With three different configurations (fig. 1), the results indicate that the distributions of void fraction follow closely an analytical solution of the diffusion equation. Further the transfer of momentum between the water jet and the surrounding air is negligible for $x/d_o < 20$ and it is not affected by the air bubble diffusion process.

An analogy with self-aerated open channel flows is further developed. The distributions of air bubble frequency have the same shape for both flow situations suggesting some similarity in the air-water flow structure. Both flow situations are characterised by a gradual diffusion of air bubbles (in the longitudinal direction) although the characteristics of the shear flow are significantly different.

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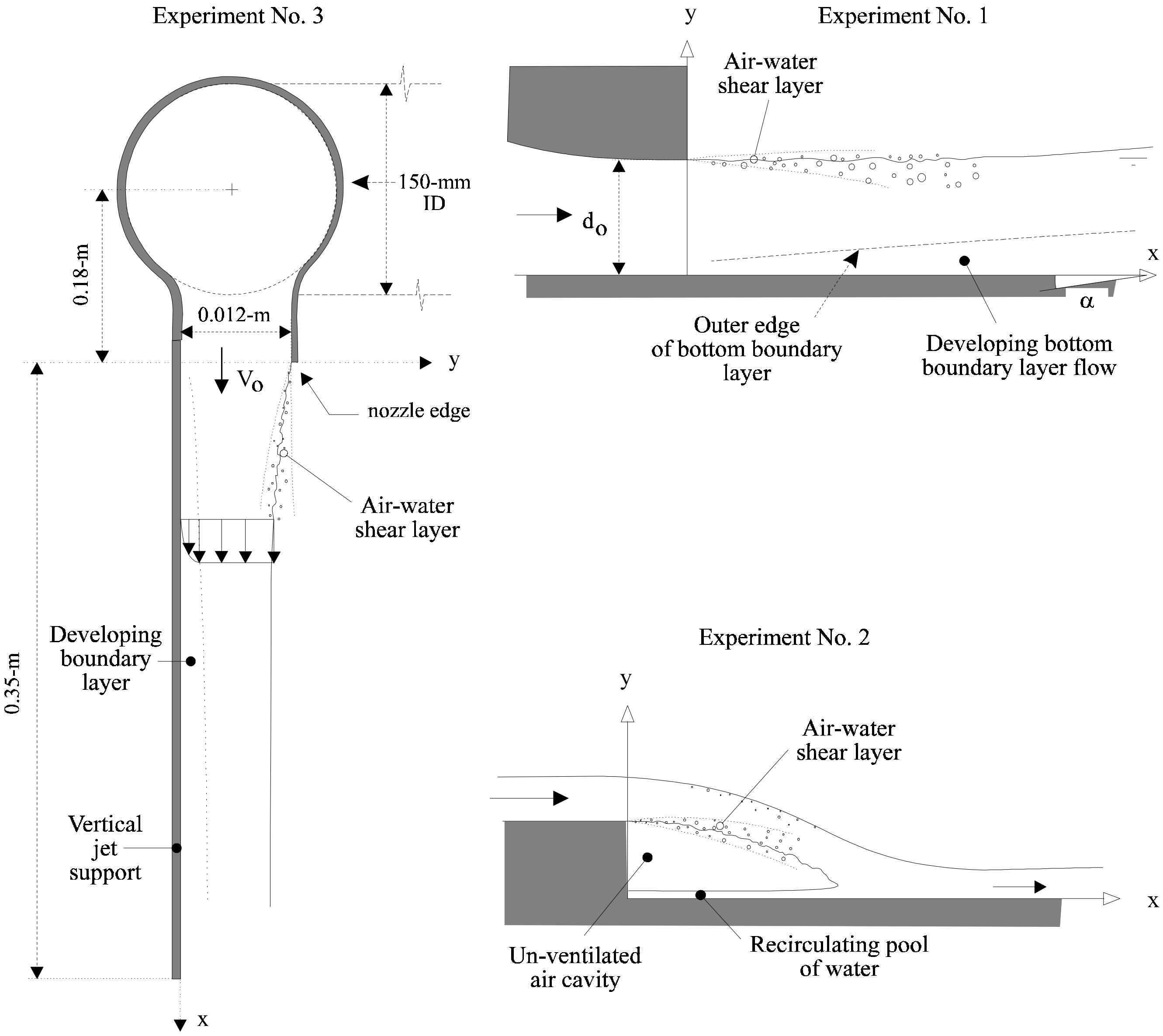
Table 1 - Experimental flow conditions (University of Queensland)

Ref. (1)	Slope α (deg.) (2)	Deflector and nozzle geometry (3)	V_o (m/s) (4)	d_o (m) (5)	Comments (7)
Experiment No. 1	4.0	Elliptical convergent (10:1 contraction in flow thickness and 2.2:1 in jet width).	5.0	0.03	Water wall-jet discharging into air. W = 0.5 m.
Experiment No. 2	0	Elliptical convergent (10:1 contraction in flow thickness and 2.2:1 in jet width).	5.0	0.03	Nappe flow at an abrupt drop (Δz = 0.131 m). W = 0.5 m.
Experiment No. 3	89	S-shaped convergent (12.5:1 jet contraction followed by a 50-mm straight section).	1.43 to 7.88	0.012	Vertical free-falling supported jet. W = 0.269 m.


Experiment No. 3

Experiment No. 1

Experiment No. 2

Fig. 1 - Air entrainment in a two-dimensional jet discharging into atmosphere

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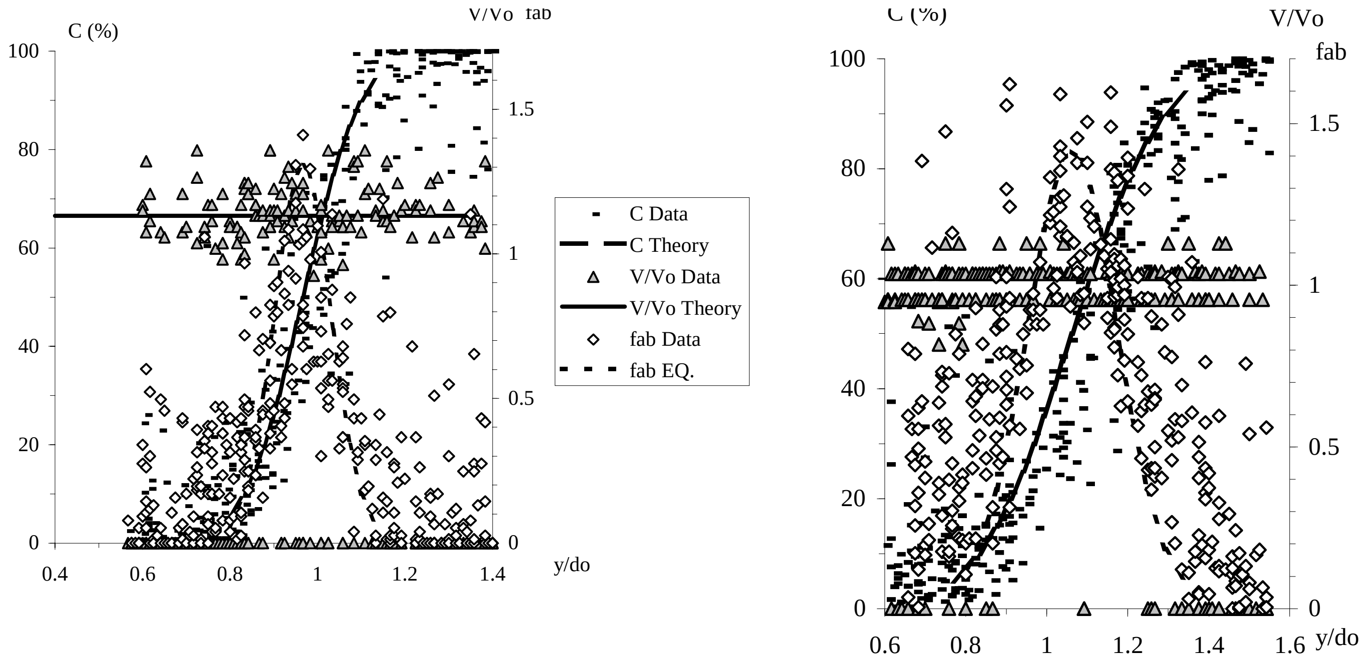

Fig. 2 - Air-water flow characteristics in free-falling jets: distributions of air concentration C, dimensionless mean air-water velocity V/V_o and dimensionless bubble frequency $f_{ab} = F^* \sqrt{x^* d_o} / V_o$

(A) $V_o = 2.65$ m/s, $d_o = 0.012$ m, $x/d_o = 8.3$ (B) $V_o = 6.86$ m/s, $d_o = 0.012$ m, $x/d_o = 8.3$

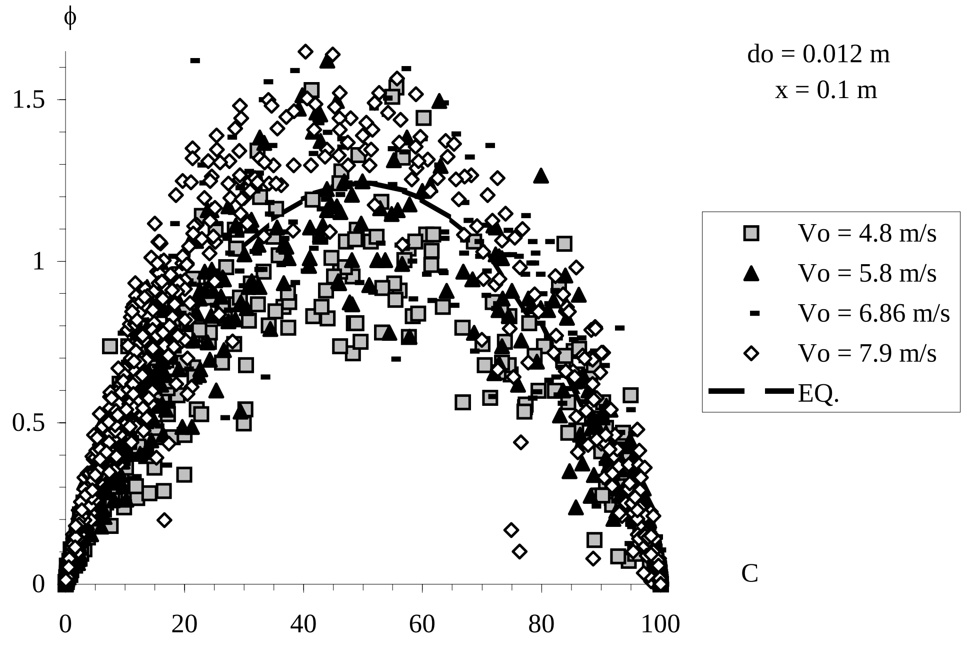

Fig. 3 - Dimensionless bubble frequency $\phi = F^* \sqrt{x^* d_o} / V_o$ as a function of the air content C

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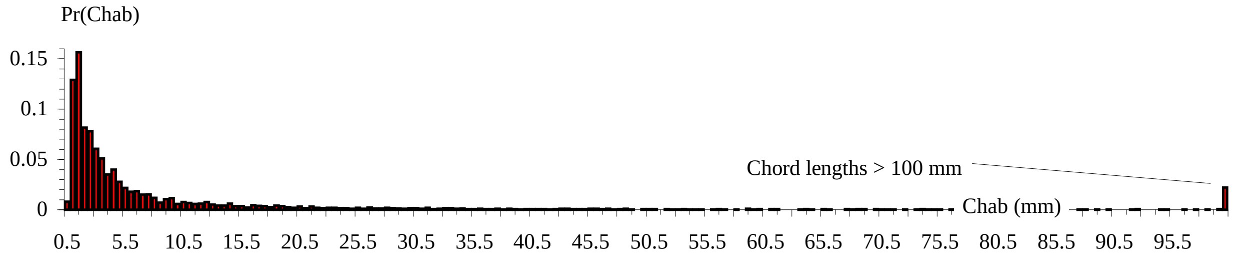
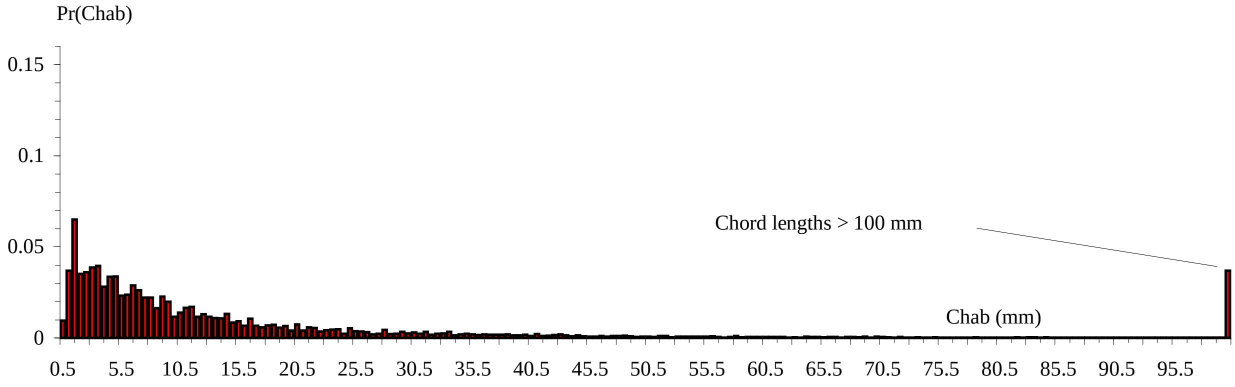


(A) x = 0.05 m



(B) x = 0.15 m

Fig. 4 - Bubble chord length distributions for V_O = 3.75 m/s and d_O = 0.012 m (Chord length interval: 0.5 mm)

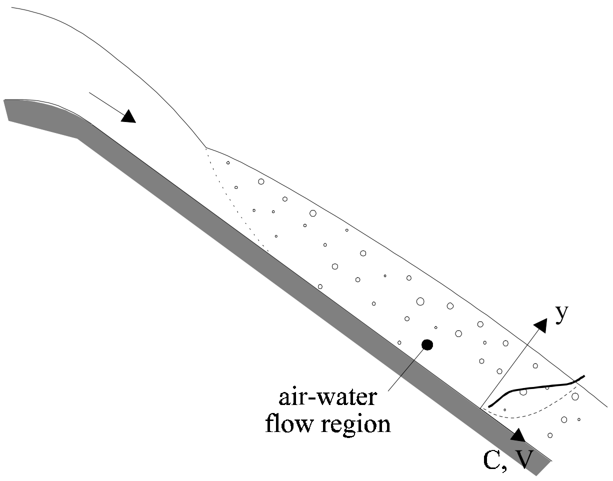


Fig. 5 - Sketch of self-aerated flows

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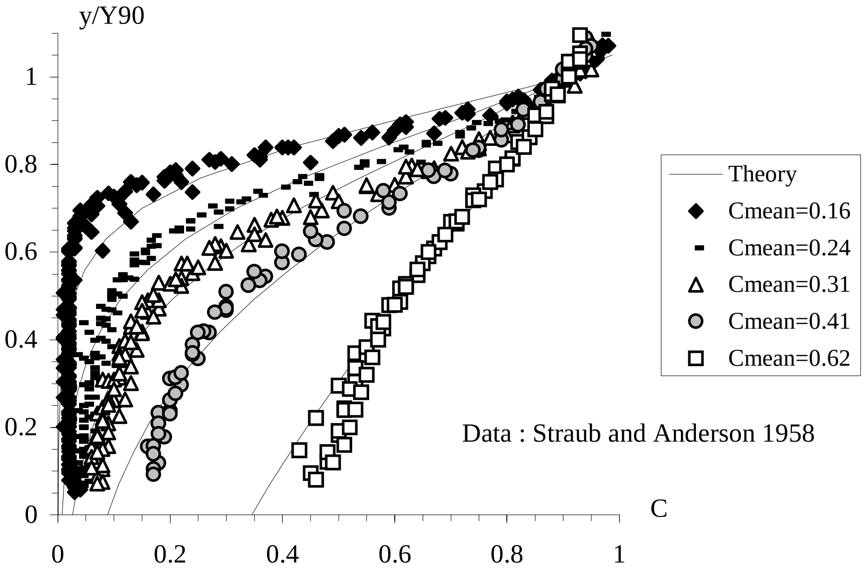

Fig. 6 - Air concentrations in self-aerated flows (Data : STRAUB and ANDERSON 1958)

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