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AIR BUBBLE ENTRAINMENT IN HYDRAULIC JUMPS WITH PARTIALLY DEVELOPED INFLOW CONDITIONS

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1. INTRODUCTION

In open channels, the transition from a rapid to fluvial flow is called a hydraulic jump. It is characterised by the development of large-scale turbulence, surface waves and spray, energy dissipation and air entrainment. The air is entrained at the jump toe into a free shear layer, characterised by intensive turbulence production, predominantly in vortices with axes perpendicular to the flow direction. Applications of hydraulic jumps include energy dissipation (e.g. stilling basin), air entraining device (e.g. in siphon), mixing device (e.g. for water treatment). The flow characteristics of a hydraulic jump are not only functions of the upstream Froude number but also of the inflow conditions. For a hydraulic jump in a horizontal rectangular channel, three types of inflow conditions are distinguished : a *partially developed* supercritical flow, a *fully developed* boundary layer flow and a *pre-entrained* jump.

In this paper, new experimental data of air content in hydraulic jumps are presented (Table 1). The experiments were performed in a rectangular horizontal channel with partially-developed upstream shear flow conditions (fig. 1). The results provide new information on the air distribution within the hydraulic jump. Full details of the experimental apparatus and approach flow conditions were reported elsewhere (CHANSON and QIAO 1994).

2. EXPERIMENTAL APPARATUS

New experiments were performed in a 3.20-m long channel of uniform rectangular section (width W = 0.25 m). Both walls and bed are made of glass (3.20-m long panels) and the channel is horizontal. Regulated flows are supplied through an adjustable vertical sluice gate. During the experiments, the gate opening was fixed at 20 mm. The experimentally observed values for the coefficient of contraction (i.e. vena contracta) were equal to 0.6 : i.e., the flow depth immediately downstream of the gate was 12 mm during the experiments. These observations are very close to the VON MISES' (1917) solution for the no-gravity case. Tailwater levels were controlled by an overshoot sharp-crested gate at the downstream end of the channel.

Air concentration measurements were performed with a single-tip conductivity probe similar as a previous design (CHANSON 1988). The probe consists of a sharpened rod (platinum wire ∅ = 0.35 mm) which is insulated except for its tip and set into a metal supporting tube (stainless steel surgical needle ∅ = 1.42 mm) acting as the second electrode. The conductivity probe was excited by an air bubble detector (AS25240) connected to a digital multimeter. The electronic circuit (i.e. air bubble detector) was calibrated with a square wave generator and it was designed with a response time less than 10 µs.

During the experiments, the location of the hydraulic jump was controlled by the downstream gate and the discharge. For all experiments, the jump toe was located at x_1 = 0.65 to 0.96 m from the sluice gate. For such locations, the turbulent boundary layer was not fully developed (CHANSON and QIAO 1994).

3. AIR BUBBLE ENTRAINMENT

Air concentration distributions were measured at the toe of the jump and along the jump. Typical profiles are plotted on figure 2. A major feature of the air concentration profiles is a region of high air content immediately downstream of the intersection of the upstream flow with the roller. A large amount of air is entrained into this region of high shear stress. As a result, the entrained air bubbles are broken up into a large number of small-size bubbles. These tiny air bubbles contribute to the enhancement of the air-water interface area and hence to the gas transfer.

Other researchers observed a similar shape of the air concentration profiles in hydraulic jumps with partially developed upstream flows : e.g. RESCH et al. (1972, 1974), THANDAVESWARA (1974). But fully developed hydraulic jumps and pre-entrained hydraulic jumps exhibit different air concentration distributions.

4. STRUCTURE OF THE BUBBLY FLOW

THANDAVESWARA (1974) presented a very comprehensive study of the bubbly flow region of a hydraulic jump. His work was conducted using high-speed photography and conductivity probe measurements. The followings summarise THANDAVESWARA's findings and is consistent with later investigations by RESCH et al. (1972, 1974), BABB and AUS (1981) and the present study.

The air-water flow of a hydraulic jump includes three regions : 1- a *turbulent shear layer* with small air bubble sizes, 2- a *"boiling" flow region* characterised by the development of large-scale eddies and bubble coalescence, and 3- a *foam layer* at the free-surface with large air polyhedra structures (fig. 1).

Air entrainment occurs in the form of air bubbles and air pockets entrapped at the impingement of the upstream jet flow with the roller. The air packets are broken up in very thin air bubbles as they are entrained. When the bubbles are diffused into regions of lower shear stresses, the coalescence of bubbles yields to larger bubble sizes and these bubbles are driven by buoyancy to the boiling region. Near the free-surface, the liquid is reduced to thin films separating the air bubbles. Their shape becomes pentagonal to decahedron as pictured by THANDAVESWARA (1974).

5. CHARACTERISTICS OF THE TURBULENT SHEAR LAYER

In the turbulent shear layer, the air concentration distribution exhibits a characteristic shape with a highly aerated core (fig. 2). The analysis of several sets of experimental data (table 1) shows that the air concentration distribution in the turbulent shear region follows a Gaussian distribution :

$$C = C_{max} * \exp\left(- \left(0.8063 * \frac{y - y_{C_{max}}}{\Delta Y_{85\%}} \right)^2 \right) \qquad (1)$$

where C_{max} is the maximum air bubble concentration in the shear layer, $y_{C_{max}}$ is the location of the maximum air content, $\Delta Y_{85\%}$ is the 85%-band width (i.e. where $C = 0.85*C_{max}$). Equation (1) is compared with the data on figure 2.

The experimental results indicate that the maximum air content in the shear layer decays exponentially with the distance along the jump. And it is best fitted by :

$$\frac{C_{max}}{(C_{max})_1} = \left(1 - \frac{x - x_1}{L_a} \right)^{1.993*Fr_1 - 6.083} \qquad \text{\{Data : present study\}} \quad (2)$$

The other main parameters of the air concentration distribution can be correlated by :

$$(C_{max})_1 = 0.2 * (V_1 - 0.8) \qquad \text{\{Data : present study, RESCH and LEUTHEUSSER 1972\}} \quad (3)$$

$$\frac{y_{C_{max}} - d_1}{d_2 - d_1} = 1.101 * \frac{x - x_1}{L_a} \qquad \text{\{present study, THANDAVESWARA 1978\}} \quad (4)$$

$$\frac{\Delta Y_{85\%}}{d_1} = 0.07435*\frac{x - x_1}{d_1} + 0.324 \qquad \text{\{present study, RESCH and LEUTHEUSSER 1972\}} \quad (5)$$

where $(C_{max})_1$ is the initial maximum air concentration, x is the distance along the channel, x_1 is the distance between the gate and the toe of the jump, d_1 and d_2 are the initial depth and its conjugate depth respectively, and L_a is the aeration length. Equation (5) is compared with experiments on figure 3.

Note that the shape of the air content distribution is similar to an advection solution downstream of an "air bubble" source (i.e. the jump toe).

6. DISCUSSION

The turbulent shear region contributes substantially to the air-water as transfer at a hydraulic jump : its large air content and the small bubble sizes resulting from large turbulent shear stress create a region of very large air-water interface area. The large air-water interface area enhances the gas transfer process.

The author (CHANSON and QIAO 1994) developed a simple model of the air-water gas transfer at hydraulic jumps with partially developed inflow conditions. It was shown that the turbulent shear region plays a major role in the gas transfer process.

7. CONCLUSION

Hydraulic jumps are characterised by a strong air bubble entrainment at the jump toe. The 'advection' of air bubbles within the jump is a complex function of the upstream flow conditions. The air-water flow of hydraulic jumps with partially developed inflow is characterised by a turbulent shear region with a large air content which contributes to enhance the air-water gas transfer in the jump.

The turbulent shear region exhibits a maximum air content which decays exponentially along the jump. The initial maximum air content is approximately proportional to the upstream flow velocity, and the rate of decay is a function of the upstream flow conditions.

Table 1 - Experimental Flow Conditions

Ref. (1)	Run (2)	q_w m^2/s (3)	Fr_1 (4)	x_1 m (5)	Comments (6)
Present study	C0	0.0504	8.11	0.963	W = 0.25 m.
	C1	0.050	8.04	0.94	
	P10	0.0420	6.05	0.890	
	C2	0.0352	5.66	0.669	
	C3	0.0312	5.02	0.696	
RESCH and LEUTHEUSSER (1972)		0.0339	2.98 (a)		Partially developed inflow.
		0.0718	8.04 (a)		W = 0.39 m.
THANDAVESWARA (1974)	R1	0.0302	7.16		Normal hydraulic jump.
	R2	0.03484	7.41		W = 0.6096 m.
	R3	0.04184	12.12		
	R4	0.04887	12.52		
	R5	0.05612	13.31		
	R6	0.06086	10.33		

Note : (a) : RESCH and LEUTHEUSSER (1972) indicated $Fr_1 = 2.85$ and 6.0. A re-analysis of their data suggests that $Fr_1 = 2.98$ and 8.04

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LIST OF SYMBOLS

C	air concentration defined as the volume of air per unit volume;
C_{max}	maximum air concentration in the turbulent shear region of a hydraulic jump;
$(C_{max})_1$	maximum air concentration in the turbulent shear region at the jump toe;
d	flow depth (m) measured perpendicular to the channel bottom;
d_c	critical flow depth (m) : for a rectangular channel : $d_c = \sqrt[3]{q_w^2/g}$;

Fig. 1 - Air-water flow regions in a hydraulic jump

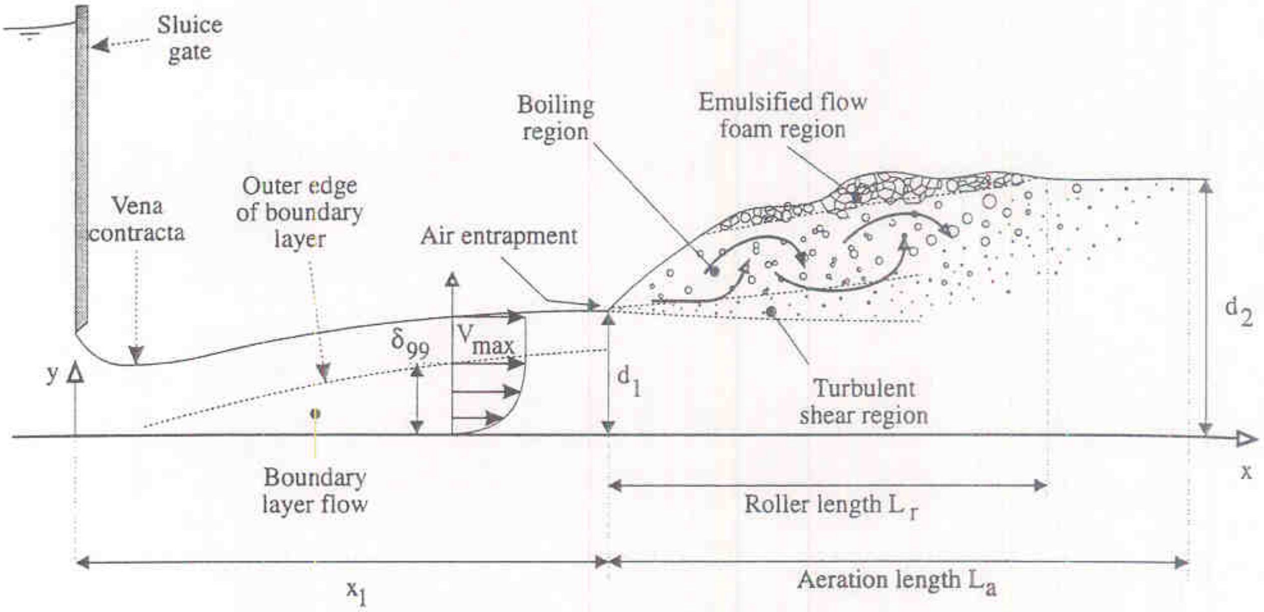
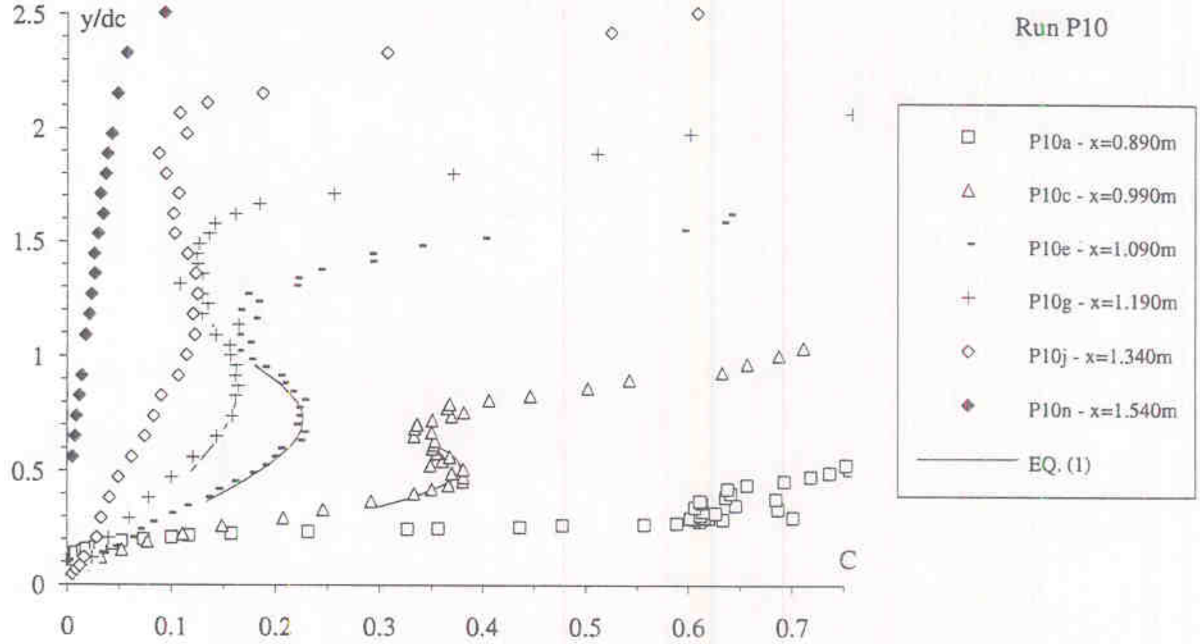


Fig. 2 - Air concentration distributions
(A) Run P10, x_1 = 0.890 m, Fr_1 = 6.05, d_c = 0.0565 m



Fr_1	upstream Froude number of the hydraulic jump;
g	gravity constant : $g = 9.80$ m/s^2 in Brisbane, Australia;
L_a	aeration length (m) of the hydraulic jump;
q_w	water discharge per unit width (m^2/s);
V	velocity (m/s);
V_1	upstream flow velocity (m/s) : $V_1 = q_w/d_1$;
W	channel width (m);

Fig. 2 - Air concentration distributions

(B) Run C2, $x_1 = 0.669$ m, $Fr_1 = 5.66$, $d_c = 0.0502$ m

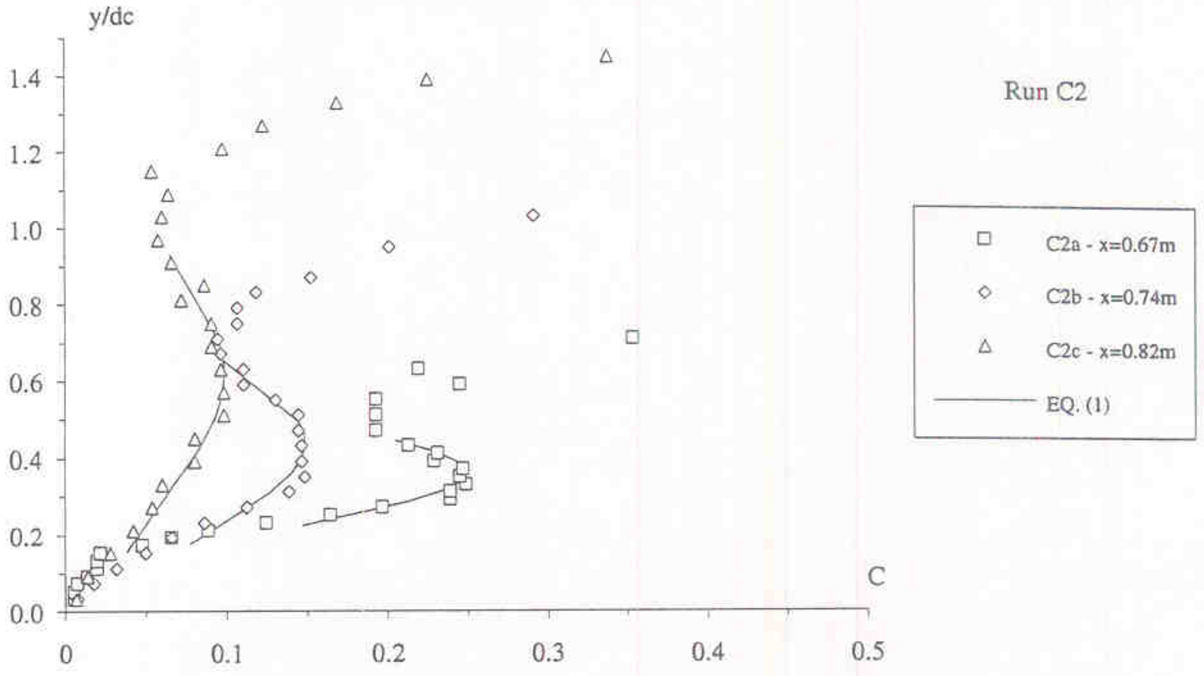
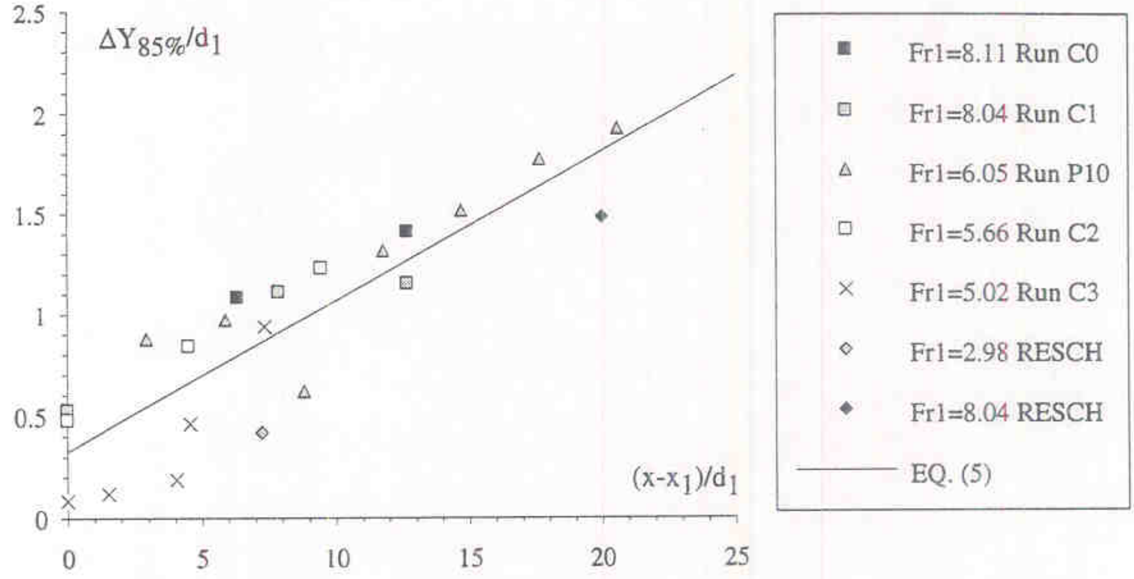


Fig. 3 - 85%-band width $\Delta Y_{85\%}/d_1$ versus the distance along the jump $(x-x_1)/d_1$



x	distance along the channel bottom (m) measured from the sluice gate;
x_1	location (m) of the jump toe measured from the sluice gate;
y	distance (m) measured perpendicular to the channel surface;
$y_{C_{max}}$	distance measured perpendicular to the channel bottom where $C = C_{max}$;
$\Delta Y_{85\%}$	85% band width (m) of the air content distribution : i.e., where $C = 0.85*C_{max}$;

Subscript

1, 2	flow conditions upstream and downstream of the hydraulic jump respectively.