AIR–WATER GAS TRANSFER AT HYDRAULIC JUMP WITH PARTICIALLY DEVELOPED INFLOW

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Abstract—In open channels, the transition from a rapid to a tranquil flow is called a hydraulic jump. It is characterized by large scale turbulence, air bubble entrainment and energy dissipation. The author has investigated the air bubble entrainment at hydraulic jumps with partially developed inflow conditions. The air–water flow is characterized by a turbulent shear region with a large air content which contributes to the enhancement of the air–water interface area and air–water gas transfer in the hydraulic jump. A new gas transfer model is presented. Based upon physical evidence, the model enables prediction of the dissolved gas contents and water quality downstream of hydraulic jumps with partially developed inflows.

Key words—air–water gas transfer, air entrainment, hydraulic jump, partially developed inflow

NOMENCLATURE

\[ a = \text{specific interface area (m}^{-1}); \text{ air–water surface area per unit volume of air and water} \]
\[ C = \text{air concentration: volume of air per unit volume of air and water} \]
\[ C_{\text{DS}} = \text{downstream dissolved gas concentration (kg/m}^3) \]
\[ C_{\text{US}} = \text{upstream dissolved gas concentration (kg/m}^3) \]
\[ C_{\text{mA}} = \text{concentration of dissolved gas in water (kg/m}^3) \]
\[ C_{\text{max}} = \text{maximum air concentration in the turbulent shear region of a hydraulic jump} \]
\[ C_{\text{max,k}} = \text{maximum air concentration in the turbulent shear region at the jump toe} \]
\[ C_{\text{ms}} = \text{gas saturation concentration in water (kg/m}^3) \]
\[ d = \text{flow depth (m) measured perpendicular to the channel bottom} \]
\[ d_{\text{o}} = \text{air bubble diameter (m)} \]
\[ (d_{\text{o}})_{\text{max}} = \text{maximum bubble size (m) in the shear flow region of a hydraulic jump} \]
\[ (d_{\text{o}})_{\text{mean}} = \text{mean bubble size (m) in the shear flow region of a hydraulic jump} \]
\[ d_{\text{c}} = \text{critical flow depth (m) for a rectangular channel: } d_{\text{c}} = \sqrt{g\frac{C_{\text{ms}}}{C_{\text{ms}}}} \]
\[ E = \text{aeration efficiency defined as: } E = \frac{1-1/r}{1} \]
\[ Fr = \text{Froude number defined as: } Fr = \frac{q_{\text{o}}}{\sqrt{g^*d_{\text{c}}}} \]
\[ Fr_t = \text{Froude number at the inception of air entrainment: } Fr_t = \frac{V_t}{\sqrt{g^*d_{\text{c}}}} \]
\[ g = \text{gravity constant: } g = 9.80 \text{ m/s}^2 \text{ in Brisbane, Australia} \]
\[ K_{\text{f}} = \text{liquid film coefficient (m/s)} \]
\[ K', \kappa' = \text{constant of proportionality} \]
\[ L_{\text{o}} = \text{aeration length (m) of the hydraulic jump} \]
\[ L_{\text{r}} = \text{roller length (m)} \]
\[ q_{\text{o}} = \text{quantity of air entrained (m}^3/\text{s) by hydraulic jump} \]
\[ Q_{\text{w}} = \text{water discharge (m}^3/\text{s)} \]
\[ Re = \text{Reynolds number: } Re = \frac{q_{\text{o}}}{v_k} \]
\[ r = \text{deficit ratio: } (C_{\text{i}} - C_{\text{us}})/(C_{\text{i}} - C_{\text{ms}}) \]
\[ T = \text{temperature (K)} \]
\[ t = \text{time (s)} \]
\[ t_r = \text{residence time (s) of air bubbles in a hydraulic jump} \]
\[ V = \text{velocity (m/s)} \]
\[ V_{\text{i}} = \text{upstream flow velocity (m/s)} \]
\[ W = \text{channel width (m)} \]
\[ x = \text{distance along the channel bottom (m) measured from the sluice gate} \]
\[ x_{\text{t}} = \text{location (m) of the jump toe measured from the sluice gate} \]
\[ y = \text{distance (m) measured perpendicular to the channel surface} \]
\[ y_{\text{CM}} = \text{distance measured perpendicular to the channel bottom where } C = C_{\text{ms}} \]
\[ x_{\text{us}}, x_{\text{us}}, x_{\text{u}} = \text{constants} \]
\[ \Delta H = \text{head loss (m)} \]
\[ \Delta Y_{\text{85%}} = \text{85%-band width (m): i.e. where } C = 0.85C_{\text{ms}} \]
\[ \delta_{\text{L}} = \text{boundary layer thickness (m) defined in terms of } 99\% \text{ of the free-stream velocity} \]
\[ v_k = \text{kinematic viscosity (m/s)} \]

subscript

\[ 1 = \text{flow conditions upstream of the hydraulic jump} \]
\[ 2 = \text{flow conditions downstream of the hydraulic jump} \]
\[ 15, 20 = \text{flow properties at 15, 20°C} \]

INTRODUCTION

In open channel flow, the transition from a rapid (supercritical) to a tranquil (subcritical) flow is called a hydraulic jump. It is characterized by the development of large-scale turbulence, surface waves and spray, energy dissipation and air entrainment. The large-scale turbulence region is usually called the "roller". The roller length can be estimated as (Hager et al., 1990):

\[ L_{\text{r}} = 8*(Fr_t - 1.5) \]

where \( d_{\text{i}} \) is the upstream flow depth and \( Fr_t \) is the upstream Froude number.

For a prismatic horizontal channel, the flow conditions downstream of a hydraulic jump are
functions typically of the discharge, upstream depth and channel shape (e.g. Henderson, 1966). However, the jump characteristics are also functions of the inflow conditions. 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. A partially developed jump exhibits a developing boundary layer and a quasi-potential flow core above (Fig. 1). For a fully-developed jump, the boundary layer has expanded over the entire flow depth. A pre-entrained jump is a fully-developed jump with free-surface aeration. The air-water mixture next to the free-surface modifies the jet impingement and hence the roller characteristics.

With any inflow configuration, large quantities of air are entrained at the toe of a jump. Air bubbles are entrapped by vortices with axes perpendicular to the flow direction. The entrained bubbles are advected downstream into a free shear layer characterized by intensive turbulence production before reaching the free-surface and escaping to the atmosphere. A re-analysis of the data of Rajaratnam (1962, 1967) showed that the aeration length can be estimated as (Hager, 1992):

\[
\frac{L_a}{d_i} = 3.5 \sqrt{Fr_t - 1.5} \tag{2}
\]

where \(d_i\) is the downstream flow depth (Fig. 1).

Several studies (Table 1) showed that the quantity of air entrained can be estimated as:

\[
Q_{ai} = K' (V_t - V_e)^n \tag{3}
\]

where \(V_t\) is the inflow velocity and \(V_e\) is the velocity at which air entrainment commences. Experimental results with hydraulic jumps (Table 1) and at vertical plunging jets (Ervine et al., 1980) suggest that the inception velocity \(V_e\) is almost constant for turbulent flows with typical values of about 0.8-1 m/s. In engineering practice, equation (3) is estimated using the correlations of Rajaratnam (1967) and Wisner (1965).

Air entrainment at hydraulic jumps has been recognized recently for its contribution to the

<table>
<thead>
<tr>
<th>Reference</th>
<th>Geometry</th>
<th>(V_t) (m/s)</th>
<th>(Q_{ai}/Q_e)</th>
<th>Comments</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalinske and Robertson (1943)</td>
<td>Hydraulic jump in a horizontal circular pipe</td>
<td>1.0</td>
<td>0.0066*(Fr_t-1)^n</td>
<td>Model data. 2 &lt; Fr_t &lt; 25</td>
<td></td>
</tr>
<tr>
<td>Wisner (1965)</td>
<td>Hydraulic jump in a rectangular conduit</td>
<td>Fr_t = 1</td>
<td>0.014*(Fr_t-1)^n</td>
<td>Prototype data. 5 &lt; Fr_t &lt; 25</td>
<td></td>
</tr>
<tr>
<td>Rajaratnam (1967)</td>
<td>Hydraulic jump in a rectangular channel</td>
<td>0.18*Fr_t-1)(^{3/2})</td>
<td>Model data. 2.4 &lt; Fr_t &lt; 8.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casteleyn et al. (1977)</td>
<td>Siphon of square cross-section</td>
<td>0.8</td>
<td>(Q_{ai} = \frac{8}{3} \pi \delta_{ij} )</td>
<td>Model data ((W = 0.43) and 0.15 m). 1 &lt; (V_t &lt; 2.8) m/s</td>
<td></td>
</tr>
<tr>
<td>Ervine and Ahmed (1982)</td>
<td>Two-dimensional vertical dropshaft</td>
<td>0.8</td>
<td>0.00045*(Fr_t-1)^n</td>
<td>Model data. Vertical jets. 3 &lt; (V_t &lt; 6) m/s</td>
<td></td>
</tr>
<tr>
<td>Rabben et al. (1983)</td>
<td>Hydraulic jump in horizontal pipes</td>
<td>Fr_t = 1</td>
<td>0.03*(Fr_t-1)^n</td>
<td>Model data. Gate opening: 1/4</td>
<td></td>
</tr>
<tr>
<td>Chanson (1993)</td>
<td>Hydraulic jump in a rectangular channel</td>
<td>0.66-1.41</td>
<td>(W = 0.25) m. Fully developed upstream shear flow</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(Fr_t = \) Froude number defined in terms of the inception velocity: \(Fr_t = V_t/\sqrt{g'd_t}\)
Air–water gas transfer at hydraulic jump

### EXPERIMENTAL APPARATUS

New experiments were performed in a 3.20-m-long horizontal glass channel (0.25-m width). Waters were supplied from a head tank which feeds the channel through a vertical sluice gate (opening: 20 mm) and the observed flow depth immediately downstream of the gate was 12 mm. Such a contraction ratio is very close to the Von Mises' solution for the no-gravity case (e.g. Henderson, 1966) and to computational calculations (e.g. Isaacs and Allen, 1994). Tailwater levels were controlled by an overflow gate at the downstream end of the channel. Further details were provided by Chanson and Qiao (1994).

The flow depths were measured using a rail mounted pointer gauge positioned over the centreline of the channel. Air–water transfer of atmospheric gases such as oxygen and nitrogen. At a jump, both the flow aeration and the strong turbulent mixing enhance the gas transfer. Several researchers proposed empirical correlations to predict the oxygen transfer (Table 2), but none of the studies took into account the air–water flow characteristics nor the effects of turbulence.

In this paper, new experimental data are presented. The results provide new information on the air distribution in hydraulic jumps with partially developed inflow conditions. Then the author proposes a new gas transfer calculation method. The model is based upon experimental observations which provide new understanding on the air–water gas transfer process. The results are compared with gas transfer data.

### EXPERIMENTAL RESULTS

Structure of the bubbly flow

Visual observations enabled a comprehensive description of the bubbly flow region of the hydraulic jump. The following summarizes the findings of the present study and the earlier investigations by Thandaveswara (1974), Resch and Leutheusser (1972), Resch et al. (1974) and Babb and Aus (1981).

The air–water flow region of the hydraulic jump can be divided into three sub-regions: (1) a turbulent shear layer with smaller air bubble sizes, (2) a “boiling” flow region characterized 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 pockets are broken up into very thin air bubbles as they are excited by an air bubble detector (AS25240) connected to a digital multimeter. The electronic circuit, designed with a response time of less than 10 μs, was calibrated with a square wave generator.

The vertical translation of the Pitot tube and conductivity probe was controlled by a fine adjustment travelling mechanism connected to a Mitutoyo™ digimatic scale unit (Ref. No. 572-503) (Δy < 0.1 mm). The longitudinal translation of the probes was controlled manually (Δx < 5 mm).

### Table 2: Oxygen transfer correlations at hydraulic jumps

<table>
<thead>
<tr>
<th>Reference</th>
<th>Formula</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holler (1971)</td>
<td>( r_{\mathit{O}_2} = 0.0463 \Delta V )</td>
<td>Model experiments: ( 0.61 &lt; \Delta V &lt; 2.44 \text{ m/s} )</td>
</tr>
<tr>
<td>Apted and Novak (1973)</td>
<td>( r_{\mathit{O}_2} = 10^{-5} \cdot \text{Fr} )</td>
<td>Model experiments: ( 2 &lt; \text{Fr} &lt; 8 )</td>
</tr>
<tr>
<td>Avery and Novak (1975)</td>
<td>( r_{\mathit{O}<em>2} = 0.23 \cdot \left( q</em>{0} \cdot 0.0345 \right) \left( \Delta H / d l \right) )</td>
<td>Model experiments: ( 2 &lt; \text{Fr} &lt; 9 \times 10^{6} )</td>
</tr>
<tr>
<td>Avery and Novak (1978)</td>
<td>( r_{\mathit{O}_2} = 4.924 \cdot 10^{-5} \cdot \text{Fr} )</td>
<td>Model experiments (W = 0.381 m) based on krypton-85 transfer: ( 1.89 &lt; \text{Fr} &lt; 9.5 \times 10^{4} )</td>
</tr>
<tr>
<td>Wilhelms et al. (1981)</td>
<td>Empirical fit based on field data from 24 hydraulic structures</td>
<td>Prototype data. Working well for deep plunge pools</td>
</tr>
</tbody>
</table>

\( \Delta V \) = difference between the upstream and downstream velocities (m/s). 
\( r_{\mathit{O}_2} \), \( r_{\mathit{N}_2} \) = oxygen deficit ratio at 15 and 20 °C.
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).

**Characteristics of the turbulent shear region**

Air concentration distributions were measured at the toe of the jump and along the jump. Typical profiles are plotted in Figs 2 and 3.

A major feature of the air concentration profiles is a region of high air content in the shear layer region immediately downstream of the intersection of the upstream flow with the roller (Figs 2 and 3). Other researchers observed a similar shape at hydraulic jumps with partially developed inflows: e.g. Resch and Leutheusser (1972), Resch et al. (1974) and Thandaveswara (1974), but fully developed hydraulic jumps and pre-entrained hydraulic jumps exhibit different air concentration distributions.

The analysis of several sets of experimental data (Table 3) shows that the air concentration distribution
Table 3. Experimental flow conditions

<table>
<thead>
<tr>
<th>Reference</th>
<th>Run</th>
<th>$q_0$ (m$/s$)</th>
<th>$Fr_1$</th>
<th>$x_0$ (m)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present study</td>
<td>C0</td>
<td>0.0504</td>
<td>8.11</td>
<td>0.963</td>
<td>$W = 0.25$ m</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>0.050</td>
<td>8.04</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P10</td>
<td>0.0420</td>
<td>6.05</td>
<td>0.890</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>0.0332</td>
<td>5.66</td>
<td>0.669</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>0.0312</td>
<td>5.02</td>
<td>0.696</td>
<td></td>
</tr>
<tr>
<td>Resch and Leutheusser (1972)</td>
<td></td>
<td>0.0339</td>
<td>2.98*</td>
<td></td>
<td>Partially developed inflow.</td>
</tr>
<tr>
<td>and Resch et al. (1974)</td>
<td></td>
<td>0.0718</td>
<td>8.04*</td>
<td></td>
<td>$W = 0.39$ m</td>
</tr>
<tr>
<td>Thandaveswara (1974)</td>
<td>R1</td>
<td>0.0302</td>
<td>7.16</td>
<td></td>
<td>&quot;Normal hydraulic jump&quot;</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>0.03484</td>
<td>7.41</td>
<td></td>
<td>with partially developed inflow.</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>0.04184</td>
<td>12.12</td>
<td></td>
<td>$W = 0.6096$ m</td>
</tr>
<tr>
<td></td>
<td>R4</td>
<td>0.04887</td>
<td>12.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R5</td>
<td>0.05612</td>
<td>13.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R6</td>
<td>0.06086</td>
<td>10.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*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.

in the turbulent shear region follows a Gaussian distribution:

$$C = C_{max} \cdot \exp\left(-\left(\frac{0.8063 \cdot \frac{y - y_{Cmax}}{A \cdot Y_{ST}}}{\frac{y - y_{Cmax}}{A \cdot Y_{ST}}}ight)^2\right)$$ (4)

where $C_{max}$ is the maximum air bubble concentration in the shear layer, $Y_{Cmax}$ is the location of the maximum air content. Equation (4) is plotted in Figs 2 and 3.

The experimental results indicate that $C_{max}$ decays exponentially with the distance along the jump and it is best fitted by:

$$C_{max} = (C_{max})_0 \cdot \left(1 - \frac{x - x_1}{L_a}\right)^{1.90 \cdot Fr_1 - 6.083}$$ (data: present study) (5)

The other parameters of the air concentration distribution are correlated by:

$$(C_{max})_0 = 0.143 \cdot (V_1 - 0.21)$$

(present study, Resch and Leutheusser, 1972) (6)

$$\frac{y_{Cmax} - d_i}{d_i} = 1.101 \cdot \frac{x - x_1}{L_a}$$

(present study, Thandaveswara, 1978) (7)

$$\frac{A \cdot Y_{ST}}{d_i} = 0.07435 \cdot \frac{x - x_1}{d_i} + 0.324$$

(present study, Resch and Leutheusser, 1972) (8)

where $(C_{max})_0$ is the initial maximum air concentration, $x$ is the distance along the channel and $x_1$ is the jump toe location. Note that equation (6) implies that there is no air entrainment for mean inflow velocities of less than 0.21 m/s. This result is consistent with previous observations (Table 1).

Air–water gas transfer

The turbulent shear region contributes substantially to the air–water gas 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.

With volatile gases, the air–water gas transfer is controlled by the liquid phase and the mass transfer across the air–water interface is usually estimated as:

$$\frac{d}{dt} C_{sat} = K_a \cdot a \cdot (C_i - C_{sat})$$ (9)

where $K_a$ is the mass transfer coefficient, $a$ is the specific surface area, $C_{sat}$ is the dissolved gas concentration and $C_i$ is the saturation concentration. The driving force of the gas transfer process is the concentration gradient. When $C_i$ is greater than $C_{sat}$, the gas will go into solution (i.e. dissolution). With $C_{sat} > C_i$ (i.e. supersaturation), the gas will desorb.

Assuming quasi-spherical bubbles, an estimate of the air–water interface area is:

$$a = 6 \cdot \frac{C}{d_{sa}}$$ (10)

where $C$ is a characteristic air concentration and $d_{sa}$ is a representative air bubble size.

In the turbulent shear region (Fig. 1), the bubble sizes are controlled by the turbulent breakup process. Experimental data of maximum and mean bubble sizes in the turbulent shear region have been re-analysed. The results (Fig. 4) show that the maximum bubble size decreases with increasing upstream flow velocity. Indeed the upstream flow velocity is a measure of the level of turbulent shear stress in the shear layers of the jump and the maximum bubble diameter is expected to decrease with increasing shear stress. The maximum and mean bubble sizes in the shear flow region can be correlated by:

$$(d_{sa})_{max} = 0.230 \cdot V_1^{-0.59} \quad (1.5 < V_1 < 5 \text{ m/s})$$ (11)

$$(d_{sa})_{mean} = 0.051 \cdot V_1^{-0.38} \quad (1.5 < V_1 < 5 \text{ m/s})$$ (12)

Air–water gas transfer model

At a hydraulic jump, most air bubbles are entrained in regions of quasi-atmospheric pressure and the pressure variations are small. The temperature and salinity are usually constant. Hence most flow
properties, including the coefficient of transfer (Kawase and Moo-Young, 1992) and the saturation concentration, become constants in equation (9).

Further, at a hydraulic jump with partially developed inflow, a major contribution to air-water gas transfer results from the small air bubbles entrained within the turbulent shear region (Figs 1, 2 and 3). In the shear region, the air-water interface area is of the order of magnitude of:

\[ a \sim 6 \frac{(C_{m\text{,}2})_{\text{max}}}{(d_{b\text{,}2})_{\text{max}}} \]  

(13)

Integration of equation (9) then yields:

\[ r \sim \exp(K_k a t) \]  

(14)

where \( t \) is the residence time of air bubbles and \( r \) is the deficit ratio. To a first approximation, the residence time can be approximated as:

\[ t \sim 2 \frac{L_a}{V_1} \]  

(15)

Equation (15) assumes that the air bubbles are entrained with a mean velocity equal to \( V_1/2 \) over the aeration region.

With these assumptions, an estimate of the air-water gas transfer at a hydraulic jump becomes:

\[ r \sim \exp \left(12K_k a \frac{(C_{m\text{,}2})_{\text{max}}}{(d_{b\text{,}2})_{\text{max}}} \right) \frac{L_a}{V_1} \]  

(16a)

where \( (C_{m\text{,}2})_{\text{max}}, (d_{b\text{,}2})_{\text{max}}, L_a, \) and \( V_1 \) are functions of the inflow conditions only and \( K_k \) is a function of the fluid properties. Replacing with equations (1), (6) and (11) yields:

\[ r \sim \exp \left(13.057 K_k \frac{V_1^{0.15}}{g} \right) \frac{(V_1 - 0.210)^*}{(\sqrt{1 + 8*Fr_1 - 1)}*(Fr_1 - 1.5)} \]  

(16b)

Equations (14) and (16) enable estimation of the gas transfer at a hydraulic jump with partially developed inflow.

**DISCUSSION**

Equation (16) has been compared with the data of Wilhelms et al. (1981). Wilhelms et al. injected concentrated solutions of krypton-85 upstream of a hydraulic jump and they recorded the downstream gas concentration. The saturation concentration for krypton-85 is zero and their experiments basically analysed the desorption of the gas. The mass transfer coefficient has been estimated using the correlation of Kawase and Moo-Young (1992) with a molecular diffusivity of krypton-85 in water of \( 1.92 \times 10^{-7} \text{ m}^2/\text{s} \) at 25°C (Hayduk and Laudie, 1974).

The results are presented in Fig. 5 where the aeration efficiency*, computed with equation (16), is compared with the experimental data of Wilhelms et al. (1981). All the data were adjusted to 25°C using the correlation of APHA et al. (1989). Figure 5 shows a reasonable agreement between the data and computations. Some scatter is observed for the largest efficiencies and Froude numbers. At large Froude number, the air entrainment is important and visual

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*More exactly the "de-aeration" efficiency.
observations indicate the existence of air pockets in which several air bubbles share the same interface. Bubble coalescence is also plausible. These mechanisms would induce a lower air–water interface [than predicted by equation (13)] and a smaller rate of aeration, but the differences between data and calculation might also result from measurements errors: Wilhelms et al. (1981) stated that “the reaeration rate coefficients vary greatly for replicate tests” and suggested additional tests at high Froude numbers.

Further, Fig. 6 shows a comparison of oxygen transfer calculations between the correlations of Avery and Novak (1978) and Wilhelms et al. (1981) and equation (16). The comparison is done within the range of the experimental studies (Table 2). The new model predicts an oxygen transfer of the same order of magnitude as experimental observations. Substantial differences are noted for large Froude numbers. These might be caused by a modification of the air–water flow structure (e.g. air pocket, coalescence) at large velocities but also by experimental errors: both
the data of Avery and Novak (1978) and Wilhelms et al. (1981) exhibited large errors for the largest Froude numbers.

CONCLUSION

In this study, the air bubble entrainment at hydraulic jumps with partially developed inflow has been investigated. The air–water flow is characterized by a turbulent shear region with a large air content. The turbulent shear region contributes substantially to the air–water gas transfer at the jump: its large air content and the small bubble sizes resulting from large turbulent shear stress create a region of large air–water interface area.

A new gas transfer model is developed based upon the air–water flow characteristics in the turbulent shear region. The new model shows a reasonable agreement with existing data. As the gas transfer model [equation (16)] is based upon physical evidence, it is believed that the new model will enable better gas transfer predictions on prototypes than existing empirical correlations. Further, equation (16) can be applied to any volatile gas and to both dissolution and desorption situations.

It must be noted that additional experiments are required for large Froude numbers and on prototypes to confirm the validity of the model.

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