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STREAM REAERATION IN NONUNIFORM FLOW: MACROROUGHNESS ENHANCEMENT[a]

Discussion by Hubert CHANSON[b] and Luke TOOMBES[c]

The authors presented two papers which are a welcome addition to the topic of water quality and stream re-aeration. The renewal theory and small eddy model provides interesting results for smooth and small-roughness channels. The discussers feel however that the second paper highlights some limits of the method, particularly when free-surface aeration takes place.

The present discussion provides additional material on the problem of stream re-aeration in presence of 'white waters' (i.e. air bubble entrainment). It complement the original paper and some references are added including large-scale data.

MASS TRANSFER EQUATION AND AIR-WATER INTERFACE AREA

The mass transfer rate of a chemical across an interface varies directly as the coefficient of molecular diffusion and the negative gradient of gas concentration. If the chemical of interest is volatile (e.g. oxygen), the transfer is controlled by the liquid phase and the gas transfer of the dissolved chemical across an air-water interface is rewritten usually as :

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[a] by MOOG, D.B., and JIRKA, G.H., *Jl of Hyd. Engrg.*, ASCE, 1999, Vol. 125, No. 1, pp.11-16.

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$$\frac{\partial}{\partial t} C_{gas} = k_L * a * (C_{sat} - C_{gas}) \tag{1A}$$

where k_L is the liquid film coefficient, a is the specific surface area defined as the air-water interface area per unit volume of air and water, C_{gas} is the local dissolved gas concentration and C_{sat} is the concentration of dissolved gas in water at equilibrium (e.g. GULLIVER 1990).

Equation (1A) is more general than the authors' equation (1) because it accounts for the variations of dissolved gas concentration in the cross-section as well as the effects of hydrostatic pressure on the equilibrium concentration. More importantly Equation (1A) includes the effect of air bubble entrainment and the drastic increase in interfacial area. Experimental measurements in supercritical flows down a flat chute recorded local specific interface area of up to 110 m^2/m^3 (m^{-1}) with depth-averaged (bulk) interface area ranging from 10 to 21 m^{-1} (CHANSON 1997). Larger specific interface areas were recorded in developing shear flows. Local interface areas of up to 400 m^{-1} were observed in hydraulic jumps and maximum specific interface area of up to 550 m^{-1} were measured in plunging jet flows (CHANSON and BRATTBERG 1997). These examples illustrate the potential for aeration enhancement in presence of 'white waters' as for example in Figure 1.

CHANSON (1995) applied Equation (1A) to smooth chute spillways. Both open channel flow aeration and hydraulic jump air entrainment were considered. The results were successfully compared with the prototype data of RINDELS and GULLIVER (1990).

Experimental measurements of air-water interface area

Measurements of air-water interface area derive from the air-water flow properties including void fraction, velocity, bubble size and bubble count. In monosize bubbly flows, the air-water interface area may be estimated from the air bubble size :

$$a = 6 * \frac{C}{d_{ab}} \tag{2}$$

where C is the concentration of undissolved air (i.e. void fraction) and d_{ab} is the bubble diameter. For a non-constant bubble size distribution, the local specific interface area equals :

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$$a = \int_{0}^{+\infty} 6 * Pr(d_{ab}) * \frac{C}{d_{ab}} * d(d_{ab}) \qquad (3)$$

where $Pr(d_{ab})$ is the probability of bubble size d_{ab}.

Experimental measurements with intrusive probes (e.g. resistivity, optical fibre) do not provide bubble diameters but bubble chord length and bubble count data. For any bubble shape, bubble size distribution and chord length distribution, the mean chord length size ([1]) equals $C*V/F_{ab}$ where V is local velocity and F_{ab} is the bubble count ([2]). The specific air-water interface area may then be estimated as:

$$a = \frac{4 * F_{ab}}{V} \qquad (4)$$

Equations (2) to (4) are valid in bubbly flows. In high air content regions (C > 0.3 to 0.5), the flow structure is more complex and the result is not exactly equal to the true specific interface area. a becomes simply proportional to the number of air-water interfaces per unit length of air-water mixture (i.e. $2*F_{ab}/V$).

CASCADE RE-AERATION

A related form of aeration enhancement by macroroughness is the re-aeration cascade. Stepped cascades are very efficient because of the strong turbulent mixing associated with substantial air entrainment (e.g. Fig. 1). Downstream oxygen saturation is usually observed, and sometimes supersaturation occurs.

In-stream cascades have been be built along polluted or eutrophic streams For example, in Chicago, five re-aeration cascades were built recently to re-oxygenate the depleted waters of the Calumet waterway. In operation their aeration efficiency (corrected to a temperature of 15 Celsius) is nearly 95% (ROBISON 1994). Similarly stepped weirs are designed downstream of large dams to control the quality of water releases (e.g. nitrogen supersaturation effect). At Petit-Saut dam, French Guyana, a two steps re-aeration cascade was added to re-oxygenate the turbined waters, despite the associated energy loss. Re-aeration

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[1]That is, the number mean size.

[2]That is, the number of bubbles impacting the probe per second.

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cascades are also used for water treatment. The Montferland plant in Netherlands was designed to remove nitrate from ground water by sulphur/limestone denitrification. It includes an aeration cascade to re-oxygenate depleted waters at the end of the process (HOEK et al. 1992).

New experimental data: aeration efficiency of a stepped cascade

A new series of experiments was performed in a flat stepped cascade at the University of Queensland. The 25-m long 0.5-m wide chute was supplied with a supercritical inflow ($2.5 \le F \le 11$, $H = 0.03$ m) cascading down ten 0.143-m high steps (3.4-degree mean slope) described by CHANSON and TOOMBES (1997). The distributions of void fraction and bubble counts were recorded with a resistivity probe (inner electrode ∅ 0.35-mm). Measurements were performed on the centreline at ten longitudinal positions per step. Three steps were investigated at the upstream end, mid-way and end of the chute. The air-water interface area was calculated using equation (4) and equation (1A) was integrated to predict the aeration efficiency of the cascade. The liquid film coefficient was calculated using KAWASE and MOO-YOUNG's (1992) correlations.

The experimental data show depth-averaged specific interface area ranging from 20 to over 120 m^{-1} typically along each step, and maximum bulk specific interface area of up to 160 m^{-1} at the largest flow rate. At each step, the interface area was maximum at the impact of the free-falling nappe and in the following spray region.

The integration of the mass transfer equation (Eq. (1A)) yields aeration efficiencies for a single step ranging from 80 to 99% (in terms of dissolved oxygen) depending upon the flow rate and step location. The strongest aeration is achieved at the largest flow rate. The results imply that saturation was achieved after two steps and they highlight the aeration potential of stepped cascades at low to medium flows (e.g. Fig. 1).

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FINAL REMARK

Although many researchers including the discussers addressed the effects of air bubble entrainment on water quality, the water quality affects reciprocally the air entrainment processes. The presence of contaminants and chemicals modifies the physical properties of air and water, and hence it could affect the air entrainment processes. Dissolved gas contents might affect also the air entrainment mechanisms. For example dissolved oxygen content affects the bubble cavitation inception. The discussers believe that dissolved gas might affect the inception of air entrainment, in a similar fashion although no systematic study has been conducted yet.

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NOTATION

V = local velocity (m/s);

a = specific interface area (m^{-1});

C = local void fraction;

C_{gas} = local dissolved gas concentration in water (kg/m^3);

d_{ab} = air bubble size (m);

F_{ab} = air bubble count (Hz);

k_L = liquid film coefficient (m/s).

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Fig. 1 - In-stream re-aeration at a stepped cascade

Cunningham weir, Dumaresq river, Australia in February 1998 during a low overflow (View from right bank)