Hydraulics of Stepped Spillways, Minor & Hager (eds) © 2000 Balkema, Rotterdam, ISBN 90 5809 135 X

Air-water flow and gas transfer at aeration cascades: A comparative study of smooth and stepped chutes

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ABSTRACT: While a stepped spillway is a common design for energy dissipation purpose, aeration cascades are used for in-stream re-aeration, in water treatment plants to enhance the air-water transfer of atmospheric gases (e.g. oxygen, nitrogen) and for the removal of volatile organic components (VOC) such as methane and chlorine. The study presents new detailed characteristics of air-water flows, including interface area data, obtained in a large stepped cascade (25-m long, 0.5-m wide). A comparative analysis of air-water gas transfer rate on smooth-invert chute demonstrates that an aeration cascade is at least 10 times more efficient for re-oxygenation purposes.

1 INTRODUCTION

Aeration enhancement by macro-roughness is well-known in water treatment, and one form is the aeration cascade (Table 1). In-stream cascades have been built along polluted and eutrophic streams: e.g., along the Calumet waterway in Chicago. Similarly stepped weirs are designed downstream of large dams to control the quality of water releases (e.g. nitrogen supersaturation effect). Despite the associated hydropower loss, a two-step re-aeration cascade was added downstream of the Petit-Saut dam in French Guyana to treat turbined waters which had unacceptable high methane content. Aeration cascades are also used in water treatment for re-oxygenation, denitrification and VOC removals. Overall stepped cascades are very efficient because of the strong turbulent mixing associated with substantial air entrainment.

The present study develops a predictive model for an aeration cascade based upon measured air-water flow characteristics. The results enable an more accurate estimate of the mass transfer of volatile gas at aeration cascades.

Basic equations for mass transfer and air-water interface area

The mass transfer rate of a chemical across an interface varies directly with the coefficient of molecular diffusion and the negative gradient of gas concentration. For volatile gases in water (e.g. oxygen), the transfer is controlled by the liquid phase and it may be expressed as :

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

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). Measurements of air-water interface area are based upon the air-water flow properties :

$$a = \frac{4 * F_{ab}}{V} \qquad (2)$$

Table 1 - Re-aeration efficiency of stepped cascades

Cascade	Ref.	Purpose	Characteristics	Performances Prototype data
(1)	(2)	(3)	(4)	(5)
Calumet waterway cascades, Chicago USA	[1,5]	Five re-aeration cascades. Designed to re-oxygenate the depleted waters of the Calumet waterway.	Cascades with pooled steps : Station 1 : 11.6 m^3/s, 4 steps (h = 1 m); Station 2 : 1.59 m^3/s, 4 steps (h = 1 m); Station 3 : 13.7 m^3/s, 3 steps (h = 1.5 m); Station 4 : 13.7 m^3/s, 3 steps (h = 1.5 m); Station 5 : 16.4 m^3/s, 4 steps (h = 1 m).	$E_{15} = 0.95$ (3-steps) to 1.0 (4-steps) for q_w = 0.021 m^2/s
Canyon weir, USA	[2]	Re-aeration weir downstream of a hydropower station. Designed to re-oxygenate turbined waters.	Labyrinth weir (crest length : 118 m). Single drop (h = 1 m). Plunge pool depth : 1.9 m. Design flow conditions : 0.14 m^2/s.	$E_{15} = 0.50$ to 0.65 for $Q_w = 3$ to 14 m^3/s
Chatuge weir, USA	[2,3]	Re-aeration weir downstream of Chatuge hydroproject in the Hiwasse river (North Carolina, USA). Designed to re-oxygenate turbined waters.	Hollow broad-crested weir. Single drop (h = 2.9 m). Plunge pool depth : 1.1 m. Design flow conditions : 1.2 m^2/s.	$E_{15} = 0.63$ to 0.73 for $Q_w = 14$ to 40 m^3/s
Petit-Saut re-aeration cascade, French Guyana		Re-aeration weir downstream of Petit-Saut dam (French Guyana). Designed to re-oxygenate turbined waters and to remove methane.	Labyrinth weir. Two drops (h = 2 m each). Design flow conditions : 110 m^3/s.	Oxygen supersaturation achieved. E(methane) = 80% (initial methane level: > 10 g/m^3).
South Houlston weir, USA	[2,4]	Re-aeration weir downstream of a hydropower station. Designed to re-oxygenate turbined waters.	Labyrinth weir (crest length : 640 m). Single drop (h = 2.3 m). Plunge pool depth : 0.91 to 1.37 m Design flow conditions : $q_w \le 0.185$ m^2/s (0.11 m^2/s during turbine operation).	$E_{15} = 0.55$ to 0.70 for $Q_w = 14$ to 68 m^3/s
Montferland demonstration plant, the Netherlands	[6]	Nitrate removal from ground water by sulphur/limestone denitrification : aeration cascade to re-oxygenate depleted water at the end of the process.	3 weirs with 3 steps each (h = 0.7 m). Design flow conditions : 9.72 L/s.	

Ref.: [1] CARGILL (1994); [2] HAUSER and MORRIS (1995); [3] HAUSER et al. (1992); [4] RIZK and HAUSER (1993); [5] ROBISON (1994); [6] HOEK et al. (1992).

Notes : E_{15} : aeration efficiency (in terms of DOC) at 15 Celsius.

where V is local air-water velocity and F_{ab} is the bubble count (i.e. number of bubbles impacting the probe per second). Equation (2) derives from the mass conservation for air and it is applicable for any bubble shape, bubble size distribution and chord length distribution. In high air content regions (C > 0.3 to 0.5, C being the void fraction), the flow structure is complex and Equation (2) is simply proportional to the number of air-water interfaces per unit length of air-water mixture (i.e. $a \propto 2 * F_{ab}/V$).

2 EXPERIMENTAL FLOW CONDITIONS

Experiments were performed in two channels (Table 2). A 24-m long 0.5-m wide flume was designed with a smooth invert. Later ten 0.143-m high horizontal steps were installed. A second channel (3.2-m long) was equipped with a single step to investigate the flow aeration at the first drop. Both channels are flat waterways ($S_o \approx 0.065$ and 0.045) with supercritical inflow

Table 2 - Experimental flow conditions

Ref. (1)	Slope θ (deg.) (2)	h (3)	l (4)	q_w m^2/s (5)	V_o m/s (6)	d_o m (7)	Comments (8)
Smooth chute							
CHANSON (1997)	4.0	N/A	N/A	0.142	4.7	0.03	W = 0.5 m. Painted timber (k_s = 1 mm).
				0.150	5.0		
				0.156	5.2		
				0.164	5.5		
Stepped chute							
Series 1	3.4 (^{a})	0.1433	2.4	0.038	1.27	0.03	L = 25 m, W = 0.5 m. Horizontal timber steps. (No sidewall offset at 1st drop)
				0.080	2.7		
				0.130	4.3		
				0.150	5.0		
				0.163	5.4		
Series 2	3.4 (^{a})	0.1433	2.4	0.080	2.7	0.03	L = 25 m, W = 0.5 m. Horizontal timber steps. Sidewall offset for nappe ventilation at 1st drop.
				0.110	3.7		
				0.150	5.0		
Series 3	N/A	0.1433	N/A	0.080	3.65	0.024	L = 3.2 m, W = 0.25 m. Single horizontal perspex step and glass flume. Sidewall offset for nappe ventilation at drop.
				0.080	2.76	0.031	
				0.092	3.35	0.029	
				0.105	3.75	0.030	
				0.136	3.61	0.040	

Notes : d_o : approach flow depth; h : step height; k_s : equivalent roughness height; l : step length; q_w : water discharge per unit width; V_o : approach flow velocity; (^{a}) : longitudinal slope of pseudo-bottom formed by step edges.

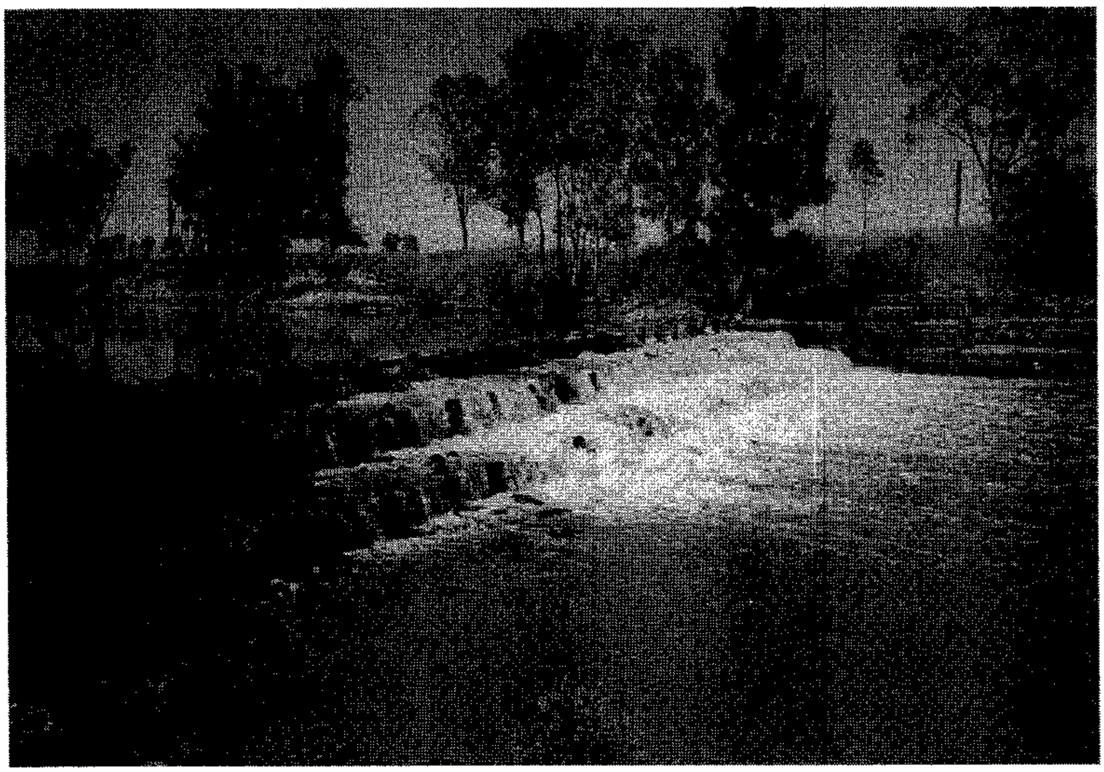
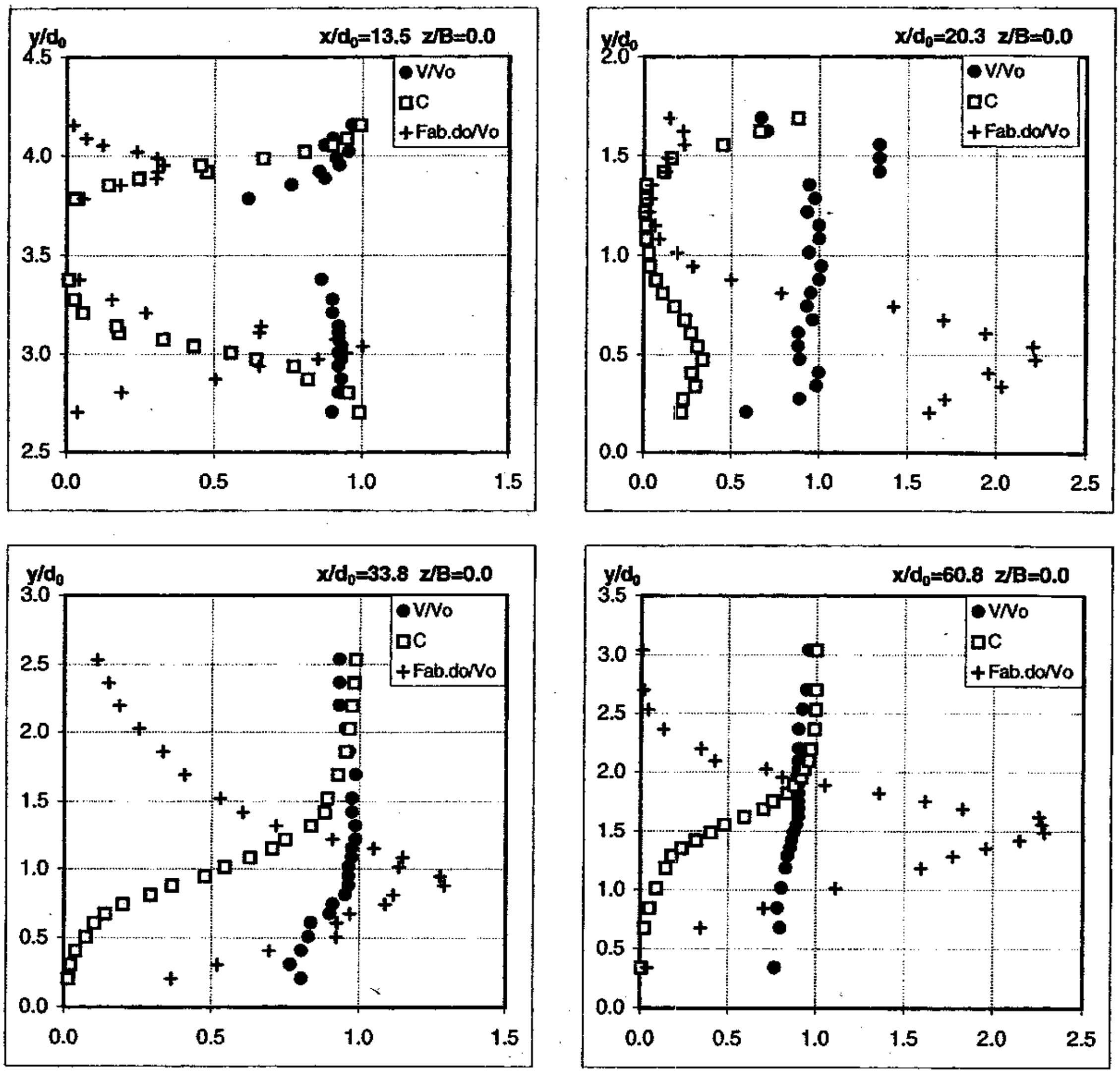


Fig. 1 - In-stream re-aeration at a stepped cascade
Cunningham weir, Dumaresq river, Australia in February 1998 during a low overflow (View from right bank)

q_w = 0.1052 m²/s, d_o = 0.0296m, h=0.143m, 1st drop, glass flume

H C, March 2000

(A) Centreline data (z/B = 0)



(B) Sidewall data (z/B = 0.48)

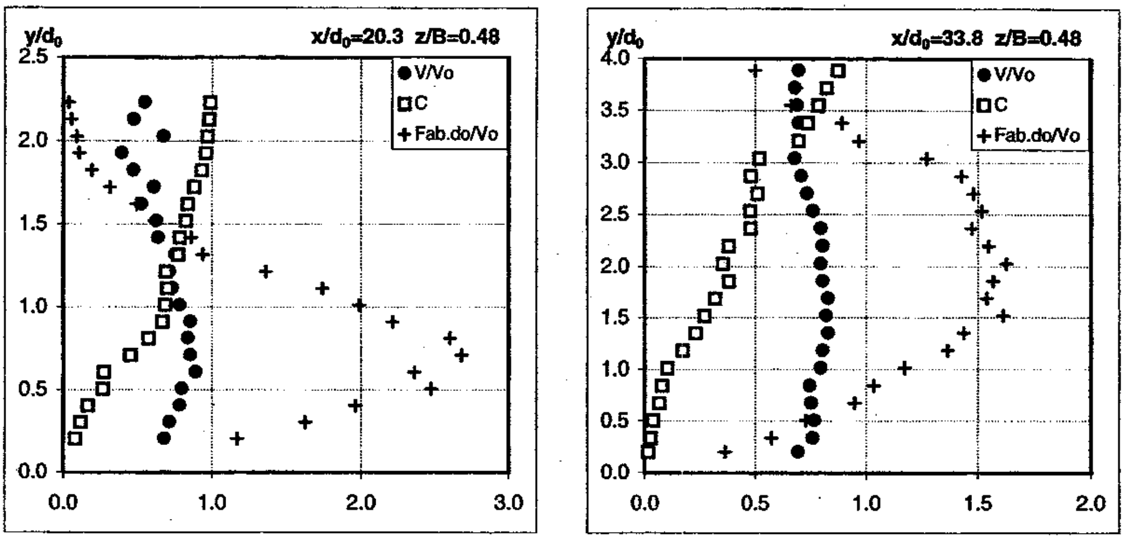


Fig. 2 - Distributions of air concentration, air-water velocity, bubble count rate

conditions : $2 \leq Fr_o \leq 10$ where Fr_o is the approach flow Froude number. The flow rates are measured with a Dall™ tube flowmeter, calibrated on site, for the 25-m long chute, and a V-notch weir in the 3.2-m long channel. The accuracy on the discharge measurement is about 2%. Clear-water flow depths and velocities were measured with a point gauge and a Prandtl-Pitot tube (Ø = 3.3 mm) respectively. Air-water flow properties were measured using either a single-tip conductivity probe (Ø = 0.35 mm) or a double-tip conductivity probe (Ø = 25 μm) developed at the University of Queensland (CHANSON 1995b). The probes are aligned in the flow direction and excited by an air bubble detector (AS25240). The resistivity probe signals were scanned at 5 kHz and 40 kHz respectively for the single-tip and double-tip resistivity probes. The translation of the probes in the direction normal to the channel invert was controlled by a fine adjustment travelling mechanism connected to a Mitutoyo™ digimatic scale unit (Ref. No. 572-503). The error on the vertical position of the probe was less than 0.025 mm. The system (probe and travelling mechanism) was mounted on a trolley system. The accuracy on the longitudinal position of the probe was estimated as $\Delta x < +/- 0.5$ cm. The accuracy on the transverse position of the probe was estimated as $\Delta z < +/- 1$ mm.

Basic flow conditions

The flow to the 24-m long flume is fed through a smooth convergent nozzle (1.7-m long), the nozzle exit being 30-mm high and 0.5-m wide. The measured contraction ratio is unity (i.e. d_o = 30 mm). Earlier experiments (CHANSON 1995b) showed that the flow is two-dimensional and fully-developed at the first drop. Water to the 3.2-m long channel is supplied via a sluice gate located 0.62-m upstream of the drop. The approach flow conditions were measured at vena contracta, and the flow was partially-developed at the step brink (i.e. $\delta/d_o = 0.2$ to 0.3, δ being the boundary layer thickness).

For all stepped chute experiments, the cascading flow was a succession of free-falling nappes with supercritical flow in between (CHANSON and TOOMBES 1997). It is a nappe flow without hydraulic jump. (Nappe ventilation by sidewall splitters was provided in the 3.2-m long flume and at the 1st drop in the 25-m long channel for experiments Series 2. The other steps were not ventilated.)

3 CASCADE RE-AERATION

The efficiency of the aeration cascade design derives from strong turbulent mixing associated with substantial air entrainment (e.g. Fig. 1). During the experiments series 2 and 3, the distributions of void fraction, bubble count, air-water velocity and bubble chord lengths were recorded with the resistivity probes. Measurements were performed at several longitudinal and transverse positions per step in the nappe and downstream of the impact. Figure 2 shows typical distributions of void fraction, air-water velocity and bubble count rates. Figure 3 presents longitudinal variations of the average specific interface area at a cross-section. Maximum interface area is consistently observed in the spray region downstream of the nappe impact. The depth-averaged specific interface area ranges from 20 to over 120 m^{-1} typically.

Equation (1) was integrated to predict the aeration efficiency of a single-step in terms of dissolved oxygen. The liquid film coefficient was calculated using KAWASE and MOO-YOUNG's (1992) correlations developed for gas bubbles affected by surface active impurities. The integration results yields aeration efficiencies ranging from 1.5 to 5 % per step, in terms of dissolved oxygen at standard conditions, depending upon the flow rate and step location. Although the specific interface area increases with flow velocity, the decreased residence time on the step results in the aeration efficiently being mainly independent of the flow rate (Fig. 4). At the first drop (Step 2), the aeration efficiency tends to decreases with increasing flow thickness (Fig. 4). The results imply an aeration efficiency of the 10-steps cascade between 15 and 40% depending upon the flow rate. [For a stepped chute with N steps of equal aeration characteristics E_1, the aeration efficiency of the cascade equals: $E = 1 - (1 - E_1)^N$ (CHANSON 1995a, p.125).] This highlights the aeration potential of stepped cascades at low to medium flows.

By comparison, the integration of Equation (1) yields an aeration efficiency of about 3 % for the 25-m long smooth-invert channel. The stepped chute design is basically 10 times more efficient than the smooth chute for the same flow rate and bed slope (per metre length of channel) !

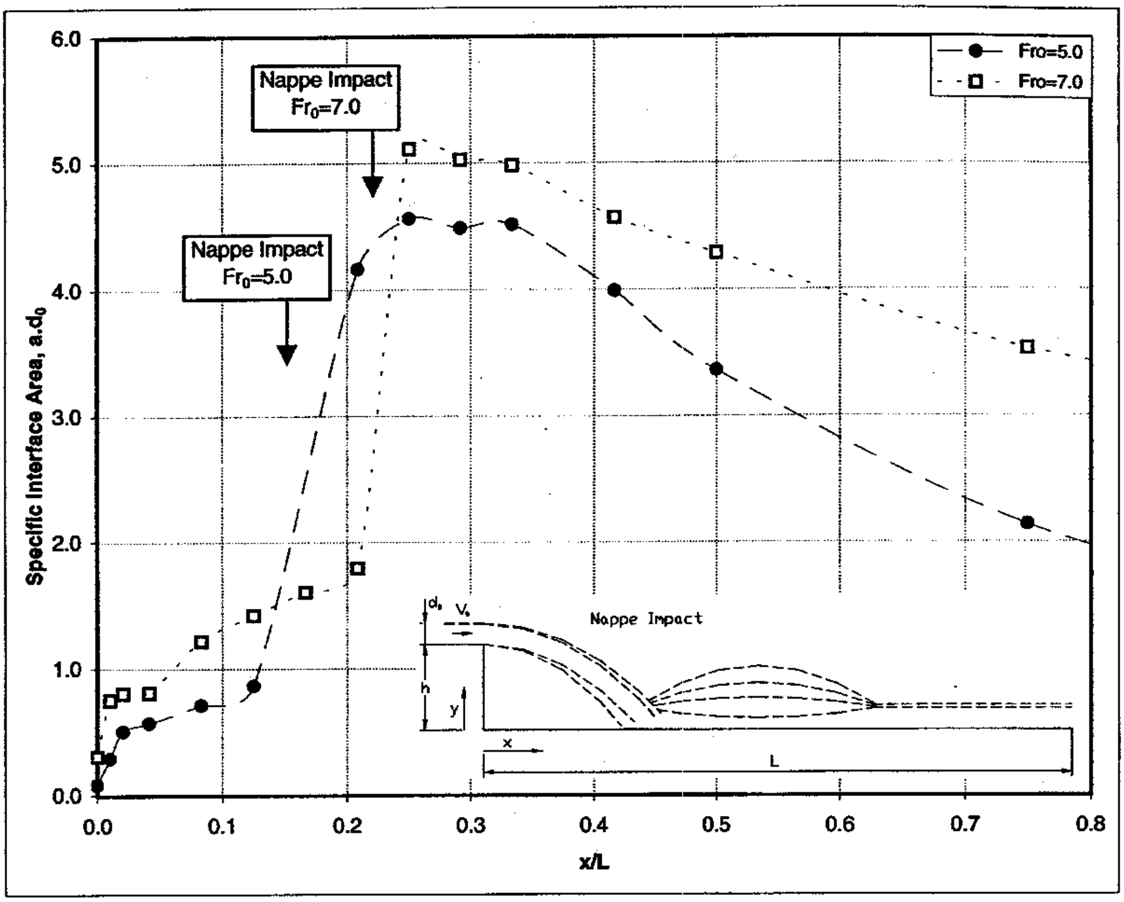


Fig. 3 - Longitudinal distributions of mean specific interface area along a step

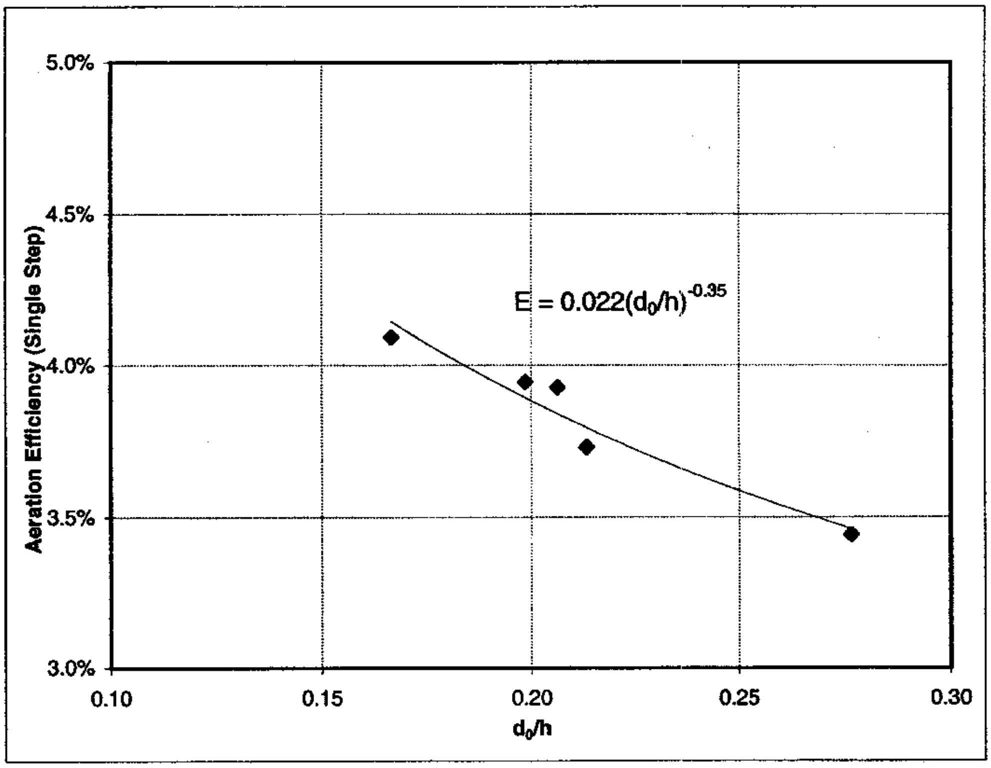


Fig. 4 - Calculated aeration efficiency (in terms of disolved oxygen at standard condtions)

4 DISCUSSION

'White waters' have great potential for aeration enhancement (e.g. Fig. 1). Experimental measurements in the smooth invert chute recorded local specific interface area of up to 110 m^{-1} with depth-averaged (bulk) interface area ranging from 10 to 21 m^{-1}. In the stepped cascade, maximum (local) specific interface area of up to 250 to 420 m^{-1} were observed. 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).
Based upon experimental observations of interfacial area, the integration of Equation (1) may provide an accurate estimate of the aeration performances of a system. The present results compare well with prototype observations (Table 1). CHANSON (1995c) applied Equation (1) to smooth chute spillways using local estimate of the specific interface area a. 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 (1989).
Although many researchers 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 writers believe that dissolved gas might affect the inception of air entrainment and amount of entrained air in a similar fashion although no systematic study has been conducted yet.

5 SUMMARY AND CONCLUSION

New measurements of the air-water flow characteristics were performed in a flat stepped cascade. The flow pattern was a nappe flow without hydraulic jumps. Maximum air-water interface area is observed in the spray region downstream of the nappe impact. Centreline and sidewall data exhibit significant differences. Overall the aeration efficiency in terms of dissolved oxygen is about 3% per 2.4-m long step, for flow rates ranging from 0.08 to 0.15 m^2/s.
For the 10-step cascade, the overall aeration efficiency is comparable with measured prototype performances (Table 1). This is about 10 times larger than for the same chute equipped with a smooth invert. The results emphasise the potential of stepped cascades for water treatment and re-oxygenation.

6 ACKNOWLEDGMENTS

The writers acknowledge the assistance of M. CONDON, L. ROWLANDS and G. ILLIDGE (University of Queensland).

APPENDIX I - NUMERICAL INTEGRATION OF AIR-WATER GAS TRANSFER

The mass transfer rate of a volatile chemical across an air-water interface may be rewritten usually as :

$$\frac{\partial}{\partial t} C_{gas} = k_L * a * (C_{sat} - C_{gas}) \qquad \text{(I-1)}$$

KAWASE and MOO-YOUNG (1991) showed that the liquid film coefficient is almost constant regardless of bubble sizes and flow conditions for gas bubbles affected by surface active impurities. Equation (I-1) may be numerically integrated between two cross-sections as :

$$\frac{\Delta C_{gas}}{C_{sat} - C_{gas}} = \frac{k_L * a}{V} * \Delta x \qquad \text{(I-2a)}$$

where a and V are respectively the mean specific interface area and flow velocity over the interval Δx. With the subscribe 1 refering to the upstream cross-section, it yields :

$$\Delta C_{gas} = (C_{sat} - C_{gas})_1 * \left(1 - \exp\left(-\frac{k_L * a}{V} * \Delta x\right)\right) \qquad \text{(I-2b)}$$

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