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Aeration efficiency over stepped cascades: Better predictions from flow regimes

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ABSTRACT

Stepped cascades are recognized as high potential air–water gas exchangers. In natural rivers, these structures enhance oxygen transfer to water by creating turbulence at interface with increasing air entrainment in water and air–water surface exchange. Stepped cascades could be really useful to improve the natural self-purification process by providing oxygen to aerobic micro-organisms. The aeration performance of these structures depends on several operating and geometrical parameters. In the literature, several empirical correlations for aeration efficiency prediction on stepped cascades exist. Most of these correlations are only applicable for operating and geometrical parameters in the range of which they have been developed. In this paper, 398 experimental sets of data (from our experiments and collected from literature) were used to develop a correlation for aeration prediction over stepped cascades derived from dimensional analysis and parameterized for each individual flow regime in order to consider change in flow regime effect on oxygen transfer. This new correlation allowed calculating the whole set of data obtained for cascades with steps heights between 0.05 m and 0.254 m, cascade total height between 0.25 m and 2.5 m, for discharges per unit of width ranging from 0.28 10^{-3} m^2/s to 600 10^{-3} m^2/s and for cascade steps number between 3 and 25. In these ranges of parameters, standard deviation for aeration efficiency estimation was found to be less than 17%. Finally, advices were proposed to help and improve the structure design in order to improve aeration.

1. Introduction

Dissolved oxygen concentration is an important indicator of water quality in natural environment. Oxygen deficit in aquatic systems occurs when water is highly polluted or in calm or stagnant canal or river. Natural water systems could have a potential to eliminate the pollution and restore ecological properties by self-purification processes. The main process requires dissolved oxygen for chemical and mainly biological mechanisms involving aerobic microorganisms. In case of O_2 deficit, biological processes and chemical oxidations are limited. Then, natural system is not able to reduce pollution concentration with harmful consequences on water quality and aquatic species. Thus, enhancing oxygenation in watercourses represents a good solution to improve self-purification process. If oxygen is spontaneously transferred by diffusion phenomenon, which depend essentially on

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Nomenclature

α	cascade slope
a	air–water interfacial area (m^2)
b	probability of nullity
C	dissolved oxygen concentration (mg/L).
C_s	dissolved oxygen saturation concentration (mg/L)
C_U	upstream dissolved oxygen concentration (mg/L)
C_D	downstream dissolved oxygen concentration (mg/L)
C_i	oxygen concentration at air–water interface (mg/L)
D_{o2}	diffusion constant of oxygen in the water ($m^2.s^{-1}$)
D, D_i	diffusivity of oxygen at T, T_i temperatures ($m^2.s^{-1}$)
E_{20}	aeration efficiency at 20 °C
Fr*	roughness Froude number as defined by Baylar et al. (2006) $Fr^* = q_W/(g.\sin\alpha.h^3)^{1/2}$
Φ	oxygen transfer rate ($mg.L^{-1}.s^{-1}$)
g	gravity constant (m/s^2)
h	step height (m)
H:	total cascade height (m)
H_e	Henry constant for O_2 (Pa. L. mg^{-1})
h_c	critical water depth (m)
K_L	water side global transfer coefficient of oxygen ($m.s^{-1}$)
K_a	air side global transfer coefficient of oxygen ($m.s^{-1}$)
K	global transfer coefficient of oxygen ($m.s^{-1}$)
l	step length (m)
L	cascade length (m)
L_a	length of aerated flow on the stepped cascade (m)
L_i	length of non aerated flow on the stepped cascade (m)
n	number of steps
Po_2	partial pressure of O_2 in the air (Pa)
q	water flowrate (m^3/s)
q_w	water flowrate per unit of width (m^2/s)
ρ, ρ_i	density of water at T, T_i temperatures ($Kg.m^{-3}$)
R_H	inflow hydraulic radius (m) = the ratio of the cross sectional area to the wetted perimeter of inflow channel
r	aeration deficit ratio
Re	Reynolds number
σ, σ_i	air–water surface tension at T, T_i temperatures ($N.m^{-1}$)
T	water temperature (°C)
t	the Student test's parameter
μ, μ_i	dynamic viscosities of water at T, T_i temperatures ($Kg.\ m^{-1}.s^{-1}$)
V	water volume on the cascade (m^3)
W	channel width (m)
x	pseudo-roughness height (m)
X_i, Y_i	Baylar et al. (2007b) correlation's coefficients

concentration gradient between the two phases as well as exchange surface, this process is slow in calm water. However, oxygen transfer could be particularly accelerated by hydraulic structures such as stepped cascades. Generally, oxygen transferred on a stepped cascade is quantitatively equivalent to a transfer on several kilometers of linear streams (Baylar et al., 2006).

Artificial stepped cascades have been used for more than 3500 years. These structures were used in aqueducts in some antic Roman cities (Chanson, 2001). In civil engineering, these structures are recognized as efficient energy dissipaters used to prevent erosion and damage of dikes and dams. Moreover, stepped cascades could be used to eliminate chlorine, tastes and odors of drinkable waters (Baylar et al., 2010) and for volatile organic compounds stripping (Toombes and Chanson, 2000). The aeration potential of these structures has been extensively studied by several authors.

Gameson (1957) is one of the first authors to be interested in the aeration by stepped cascades. Since then, several authors studied oxygen transfer by these hydraulic structures. The aeration efficiency was measured by Tebbutt (1972) on a laboratory stepped cascade essentially for discharges below 4 L/s, cascade total height was of 1.8 m and a maximum steps number of 25 were tested. Essery et al. (1978) proposed a correlation to predict cascades aeration efficiency with steps height between 0.025 and 0.5 m and for discharges between 1.5 L/s and 22 L/s. Toombes and Chanson (2005) studied the oxygenation on a stepped waterway with low chute slope (about 3.4°, the steps length was about 17 time more important than steps heights) and for high discharges between 19 and 300 L/s. Baylar et al. 2006, 2007b, 2007c, 2010); Baylar and Bagatur (2007); Baylar and Emiroglu (2003) conducted a large number of water aeration experiments on laboratory stepped cascade. They characterized the oxygenation by several empirical correlations for discharges between 5 L/s and 50 L/s; cascade total height was between 1.2 and 2.5 m and maximum steps number of 50. Generally, previous correlations neglect the effects of some significant parameters and are only applicable on restricted conditions. So, Essery's correlation ignores viscosity and steps length effects. Baylar et al. correlations are purely empirical and neglect the effects of steps number on aeration.

The aim of this paper is to develop a more general correlation for aeration efficiency prediction on stepped cascade, useful for design in wide range of parameters. The experimental measures as well as the data collected in the literature are used. Dimensional analysis was used to determine the type and the number of parameters to be considered in aeration efficiency modeling.

2. Bibliographic review

2.1. *Air water mass transfer*

According to Whitman and Lewis theory of double film, the interface between two fluids can be considered as two stagnant thin films where solute transfer takes place; one on the liquid side described by the coefficient K_L and the other on the gas side (Roustan, 2003). For slightly soluble gases in water, the resistance to the transfer liquid side is much more important than the one on the gas side.