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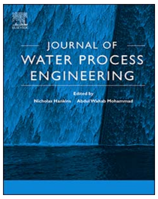

Re-aeration study of effluent from a wastewater treatment plant

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ABSTRACT

In this work, we present an experimental study on the re-aeration of a biological effluent coming from a wastewater treatment plant located at sea level. The oxygen transfer efficiency has been calculated for a hydraulic structure characterized by three different weirs jumps (Bazin type). The experimental results have been compared with those obtained by two (and well known) empirical equations (*Avery-Novak* equation (Avery and Novak, 1978) and *Thene* equation (Thene, 1988)). These equations did not allow a well fitting of the experimental data. We proposed a modification of the *Thene* equation by inserting of the Weber number of the jet. By this new correlation, we obtained a good fitting of re-aeration data obtained for the studied hydraulic structure.

1. Introduction

Water aeration is one of fundamental aspects for existence and good quality life of aquatic species. The process of re-oxygenation can be considered in at least two successive parts: (1) air absorption and (2) air mass-transfer in the water system. The absorbed and dissolved oxygen concentration in the water is function of temperature, pressure and salts content.

Moreover, the concentration of organic species in water strongly affects the oxygen consumption [3,4]. Treated water should have low dissolved oxygen content [5,6].

Because of the significant influence that a hydraulic structure has on the oxygen transfer levels, engineers are required to control and affect these levels.

Hydraulic jumps represent an economic and efficient solution to accelerate the gas solubilization processes. Moreover, the re-aeration induced by the turbulent flow caused by the jumps reduces the metals precipitation and the amount of dissolved gas, such as CO_2, H_2S, CH_4, etc., [7].

The re-aeration theory is directly related to the Henry's law. This law represents, for dilute concentrations of many gases and over a fairly wide range of some gases, the equilibrium relationships between the partial pressure developed by a dissolved solute (gas) A in a liquid solvent B, by the following equation:

$$P_A = H\, x_A \tag{1}$$

where P_A is the partial pressure of gas A in the atmosphere [hPa], H is the Henry's law constant for the gas A [hPa] and x_A is the mole fraction of gas A in the liquid [8]. In other words, the amount of dissolved gas (x_A) is proportional to its partial pressure in the gas phase (P_A). The Henry's constant depends on solute and solvent couple and is function of temperature.

In addition, the dissolved oxygen concentration is function of water salinity (S), water temperature (T), atmospheric pressure (P) and vapor pressure (p), according to the following equation [8]:

$$C_{sl}(T, S, P) = C_{sl}(T, S)\frac{P - p}{P_0 - p} \tag{2}$$

where C_{sl} is the oxygen saturation concentration at atmospheric pressure [mg/l], P is the atmospheric pressure [mmHg], p is the vapor pressure of water [mmHg], T is the temperature of the water, P_0 is the sea level pressure [760 mmHg] and S is the salinity of the water [‰].

For altitude lower than 1000 m on sea level and for temperature lower than 25 °C, the water vapor pressure p in the Eq. (2) should be omitted.

The oxygen transfer in the water is a further important aspect to consider in the water re-aeration process. This phenomenon is regulated by the molecular diffusion theory, governed by the Fick's law [9]. This law predicts that the mass transfer rate, in the steady state, is proportional to the difference between the bulk concentration and the concentration at the gas-liquid interface: gas concentration gradient across the interface.

Applying this law at a water-oxygen system, joint with the *film theory,* it is possible to obtain the interphase mass transfer rate equation [10–12]. Integrating this equation between the limits of 0 and *t* (time), and C_0 and C_e (oxygen concentration), it is possible to obtain the most used equation for the oxygen deficit ratio *r* or for the oxygen transfer efficiency *E*:

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$$E = \frac{C_o - C_e}{C_{s\,l} - C_e} = 1 - \frac{1}{r} \tag{4}$$

where C_e [mg/l] is the upstream dissolved gas concentration and C_o [mg/l] is the dissolved gas concentration at the downstream. Taking these parameters constant for atmospheric systems, it is possible to obtain the oxygen transfer efficiency E and the oxygen deficit ratio r equations at the time t [12].

The oxygen transfer efficiency that occurs at given structure is sensitive to kinetic molecular diffusion, fluid dynamic (rate, turbulance, rugosity), hydraulic structure geometry (height, spillway configuration, etc.), contact time, chemical characteristics of the water (salinity, surfactants, oxidant molecules, oils and fatty, etc.), and pressure [10,13,14].

In the presence of hydraulic structures with jumps, two mechanisms that favor the water aeration are recognized: the first regards the increasing of air-water interphase (bubbles surface) and the second considers the hydrostatic pressure effect on the bubbles dragged in the bottom of the tailwater [11,15–20].

1.1. Predictive equations

Several authors proposed empirical correlations predicting the deficit ratio r or the aeration efficiency E. These correlations have been obtained for experiments carried out on hydraulic structure in situ [21–23] or on laboratory models [11,15,24–27]. In any case, these correlations are valid only under the conditions applied during the experiment and for tested hydraulic structure.

Water aeration by overfalls jet weir is the most studied hydraulic case. *Avery and Novak* [1] gave hydraulic jumps models for weirs and cascades spillways. They noted that, for this type of hydraulic structures, the oxygen deficit ratio r, at 15 °C, is function of geometric parameters of the jet, of water-air time contact, of fluid dynamic of the jet and of water characteristic (viscosity, density, etc.). The authors used the Reynolds and Froude numbers referred to the jet (respectively Re_j and Fr_j) and defined as follows:

$$F_{rj} = \frac{(2g)^{0.25} h^{0.75}}{q^{0.5}};\ R_{ej} = \frac{q}{2\nu} \tag{5}$$

where Q is the water discharge [$m^3\,s^{-1}$], q is the specific discharge at impact into the downstream pool (Q/b) [$m^2\,s^{-1}$] (where b is the jet width [m]); h is the difference between the upstream and downstream water level (drop height) [m], μ is the water viscosity [$N\,s\,m^{-2}$], ν is the water kinematic viscosity ($\mu\,\rho^{-1}$) [$m^2\,s^{-1}$], ρ is the water density [$kg\,m^{-3}$] and g is the gravity acceleration [m/s^2].

The oxygen deficit ratio correlation proposed, r_{15}, at 15 °C, for Reynolds number values ranging from $1.45{\cdot}10^4 < Re_j < 7.1{\cdot}10^4$, for water kinematic viscosity ν equal to $1.143{\cdot}10^{-6}\,m^2\,s^{-1}$, and for drop height values ranging from $0.05 < h < 6\,q^{1/3}$ [m], is the following

$$r_{15} = 1 + k\,Fr_J^{1.787}\,Re_j^{0.533} \tag{6}$$

where k is a dimensionless coefficient, equal to $0.64{\cdot}10^{-4}$.

Novak [11] obtained k as function of water salinity. For example, he found that k is equal to $0.627{\cdot}10^{-4}$ for water without salts while, for water containing the 0.6% of $NaNO_2$, is equal to $1.243{\cdot}10^{-4}$.

Moreover, the author demonstrated that the Eq. (6) could be also applied to multiple jets and cascade weirs. Particularly, at the same drop height, the oxygen transfer increases at the steps cascade number increasing. For n equal steps, the deficit ratio would be r^n, where r is the deficit oxygen ratio of each step, at 15 °C.

Further studies demonstrated that the model proposed by *Avery and Novak* [1] (Eq. (6)) well predicts the deficit ratio values obtained by laboratory measurements [13,28,29].

The oxygen deficit ratio is sensitive to the water temperature; for this reason *Avery and Novak* [1] proposed to use the following equation:

$$\frac{r_T - 1}{r_{T0} - 1} = \frac{(1 + 0.046T)}{(1 + 0.046T_0)} \tag{7}$$

where r_T is the oxygen deficit ratio at the temperature T, T_0 is the reference temperature (generally 15° or 20 °C) and r_{T0} is the oxygen deficit ratio at T_0.

In the meantime some authors proposed different temperature correction factors. *Gulliver* et al. [28] suggested to calculating the aeration efficiency, at the temperature T of the measurement, using a temperature correction factor λ, according to the Eq (8)*:*

$$r_t = r_{20}^{\lambda} \tag{8}$$

where λ is described by the following equation:

$$\lambda = 1 + 0.02103\,(T\text{-}20) + 8.261{*}10^{-5}\,(T\text{-}20)^2 \tag{9}$$

Further important hydraulic structures parameter that affects the oxygen transfer efficiency, or the deficit oxygen ratio, is the tailwater depth (D_p) of the channel. *Avery and Novak* [1] observed that tailwater depth should be 0.6 times higher than the drop height to affect the oxygen transfer efficiency.

Thene [2] founded that the tailwater depth should be included in the formula of *Avery and Novak* [1] (6) to calculate the oxygen deficit ratio, as follows:

$$r_{15} = 1 + 1.005 \times 10^{-5}{\cdot}F_{rJ}^{\,2.08}{\cdot}R_{ej}^{\,0,63}\left(1 - 0.6\,e^{(-3.7\,\mathbf{Dp}/h)}\right) \tag{10}$$

where h is the drop height.

Avery and Novak [1] stressed that for the following values of tailwater depth (D_p), in meters,

$$D_p \geq 7.5{\cdot}h^{0.58}\,{\cdot}F_{rj}^{\,-0.53} \tag{11}$$

the influence of D_p on the oxygen transfer process is negligible.

Later, *Nakasone* [30] founded that the aeration efficiency increases with the tailwater depth, with optimal values for D_p equal to the 30% of drop height h. Values of tailwater depth higher than 2/3 of drop height do not affect the oxygen deficit ratio.

In this work, we applied the *Avery-Novak* (eq. 6) and *Thene* (eq. 10) equations to calculate the oxygen transfer efficiency of a re-aeration structure (weirs thin-wall, Bazin type) presents at the end of a wastewater treatment plant located in Diamante (CS), South of Italy. Diamante is an Italian little sea town. Therefore, the influence of the pressure on the dissolved oxygen concentration in the water, as highlighted by the Eq. (2), could be neglected. Only the water temperature, the water salinity and the hydraulic structure type affect the oxygen transfer efficiency. Analyzing the obtained results, we proposed a modification of *Thene* equation [2] by Weber number inserting, in order to obtain a better fitting between predicted and experimental data.

2. Materials and Methods

The aeration efficiency has been analyzed for a hydraulic structure characterized by jumps from weirs thin-wall, Bazin type.

The weirs have been set on a channel placed at 25 m on the sea level. The channel receives the effluent from a wastewater treatment plant and is located in Diamante (CS), South of Italy.

A schematic representation of studied hydraulic structure is shown in Fig. 1.

The hydraulic structure, that receives the water from the treatment plant by a first Bazin weir of 1256 mm wide, consists in two adjacent channels, staggered in height. The first channel was 8.0 m long, 680 mm wide and ends with a second Bazin weir that can be set in two different vertical heights (H).

At the end of each weir there is a receiving tailwater. The first weir is characterized by fixed measures of the jump (I jump: H = 1.03 m, b = 1256 mm, D_p = 0.47 m), while the second weir is characterized by two possible jump heights, to which correspond two different widths of the weir (b).