AERATION EFFICIENCY OF A LABORATORY FISH LADDER MODEL

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The paper presents a procedure for evaluating the aeration efficiency AE in free-surface flows, applicable to laboratory fish ladder models.

Oxygen transfer across air-water interface was studied experimentally in a fish ladder model with baffles and pools. The experiments were carried out for five scenarios, meaning specific type and arrangements of baffles, for which both hydraulic and aeration parameters (oxygen transfer rate and aeration efficiency) were determined. The present study represents a modality for optimizing the design of fish ladder prototypes regarding the oxygen transfer.

Keywords: fish ladder, dissolved oxygen concentration, aeration efficiency.

1. Introduction

Fish ladders (known in literature as fishways or fish-passes) are hydraulic devices which can re-establish the longitudinal connectivity between the upstream and downstream of the river when the aquarium habitat is fragmented by dams, spill ways, thresholds and weirs. There are two main groups of fish ladders like nature (or close-to-nature) fish ladders and technical fish ladders. Different types of technical fish ladders are known: vertical slot, pool and weir, pool and orifice, Denil, elevator fishways etc. [1].

Irrespective of the fish ladder types the water quality has to remain within the environmental guidelines because the general condition of growth and health affects the aquaria life. The dissolved oxygen (DO) concentration is one of the most important parameters affecting the fish biology. For example, the minimal amount of DO for cold water is 9.5 mg/L in early life stages and 6.5 mg/L in other life stages of the aquatic life [2].

In free surface flows, reaeration is a process that takes place at the air-water interface to re-establish dissolved oxygen equilibrium. Empirical equations available to predict oxygen transfer coefficient K_L are related to natural reaeration

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across the water free surface [3]. There is hardly any data for K_L or oxygen transfer rate (*OTR*) regarding reaeration in fish ladders due to turbulence distributions induced by their design.

The aim of this study is to evaluate *OTR* and aeration efficiency (*AE*) in a laboratory fish ladder model with pools and baffles, for different scenarios, meaning type and arrangement of baffles, in order to select the scenario that ensures the highest oxygen transfer rate.

The effect of turbulence on the liquid-film coefficient K_L and consequently on oxygen mass transfer rate through air-water interface has been studied by different authors [4-7]. The velocity and turbulence patterns at the passageways of the baffles, as well as the free surface turbulence depend on the type and arrangement of baffles, therefore the scenarios taken into consideration will obviously make a difference regarding the oxygen transfer rate.

2. Experimental set-up

In order to measure the dissolved oxygen concentration in a laboratory fish ladder model, the experimental rig presented in Fig. 1 was used.

The constructive elements of the experimental rig are: (1) the flume with pools and baffles (2) supplied with water in closed circuit by the radial pump (3) from the reservoir (5); the flow rate in the flume is measured using a V-notch weir (7) experimentally calibrated [8]. The flume is split into 5 pools by removable baffles (2) which can have lateral submerged orifice or vertical slot. Each type of baffles can be arranged in line or zigzag, Fig. 1.b. Five fish ladder types will result consisting in 5 working scenarios, Table 1.

Table 1

Working scenarios regarding baffle type and arrangement

Scenarios (Aeration system)	Baffle type	Baffle arrangement
S1	Lateral submerged orifice	zigzag
S2	Lateral submerged orifice	in line
S3	Lateral vertical slot	Mixt (the first two baffles in zigzag and the last two in line)
S4	Lateral vertical slot	zigzag
S5	Lateral vertical slot	in line

The pump is controlled by the discharging valve (9). Details regarding the flume design are in references [8, 9].

The DO concentration measurements are carried out with the oximeter (4) and the optical sensor (6). The data are processed by PC (8).

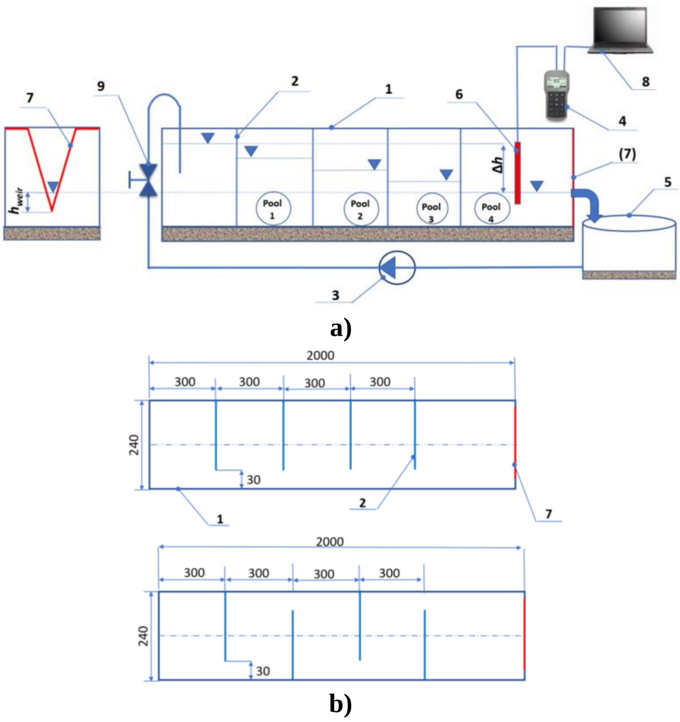

Fig. 1. Sketch of the experimental rig with the frontal view of the flume **(a)** and top view of the flume with in line and zigzag baffle arrangements **(b)**

The flume is supplied with water from the tank by the pump. The weir downstream the flume ensures the flow as well as the flow rate measurement. In the pools formed due to the baffles placed along the flume, the water has different depths as a result of the pressure losses through the submerged orifices or lateral slots of the baffles. Because these orifices and slots are identical for all baffles, the pressure losses are also identical in all the pools of the flume.

The dissolved oxygen concentration is measured *in situ*, within the pools named in Fig. 1. In the supply pool (the first pool of the flume having no name), no measurements of DO concentration were made.

3. Experimental procedure

The experiments were carried out for different baffle systems (baffle type and arrangements). The baffle system is assimilated to an aeration device operating in closed hydraulic circuit, in unsteady state regime regarding dissolved oxygen (DO) concentration and under given power conditions. The efficiency of the aeration device was determined using the guidelines of the *ASCE Standard for the Measurement of Oxygen Transfer in Clean Water* [10].

The theory used in the ASCE Standard is based on the *two-film theory* of Lewis and Whitman (1924), which states that transfer rate can be expressed in terms of an overall transfer coefficient and resistances on either side of the interface. In the case of oxygen, which has a low solubility in aqueous medium, the resistance of the gas film is neglected and only the resistance in the liquid film is considered.

The oxygen transfer can be expressed as:

$$\frac{dC}{dt} = K_L a \cdot \left(C_\infty^* - C\right), \tag{1}$$

where: K_La represents the overall volumetric mass transfer coefficient (s^{-1}), C_∞^* represents DO saturation concentration (mg/L), C represents DO concentration in the liquid phase at time t, (mg/L).

The integrated form of equation (1) is:

$$C = C_\infty^* - \left(C_\infty^* - C_0\right)\exp\left(-K_L a \cdot t\right), \tag{2}$$

where C_0 represents DO concentration at time t=0, (mg/L).

The test method proceeds as follows:

1. The test tank-represented in this case by the flume, the supply reservoir and the pipes- is filled with tap water.
2. The water volume is determined in order to calculate the necessary amount of sodium sulfite to be added for water deoxygenation (130 % of the stoichiometric requirement).
3. The oxygen is removed from the water by sodium sulfite added in solution and uniformly distributed throughout the water volume, in the presence of cobalt chloride $CoCl_2 \cdot H_2O$ as catalyst. A solution of cobalt salt is added until a concentration of 0.2 mg/L in water is achieved.
4. The number and location of DO determination points for *in situ* measurement are selected so that they best represent (vertically and horizontally) the water volume (according to ASCE Standard). In this case, four determination points are selected, one in the center of each pool (except the first pool in which the pump discharges), submerged at a depth of $\frac{1}{2}h$ from the water surface, where h represents the water depth in each pool. By selecting this pattern of determination points, whatever the case may be regarding the type and arrangement of baffles, the location of DO probe in an area of maximum turbulence is avoided.

5. The experimental set-up is operated in closed circuit to achieve steady-state hydraulic regime before starting the oxygen transfer evaluation.
6. The DO concentration is recorded at appropriate intervals during reaeration, up to 98% of the expected value of C^*_∞, using an oximeter with optic sensor (HQ40d) with continuous recorder and USB connection to PC.

The experiments were carried out for five scenarios presented in Table 1.

The operating hydraulic parameters are: the flow rate in the flume Q (L/s), the head drop between pools Δh (mm) on the entire fish ladder and the hydraulic power P_h (W). The formulae used for the calculus of the flow rate and hydraulic power are:

$$Q = 0.5353 \cdot h_{weir}^{2.3788}, \quad (3)$$

with h_{weir} the water level above the crest of the weir placed at the end of the downstream pool of the flume, and

$$P_h = \rho \cdot g \cdot Q \cdot \Delta h, \quad (4)$$

with ρ water density (kg/m^3) and g gravitational acceleration (m/s^2).

The head drop between pools Δh was measured as difference between the water level in the first and the last pool and the h_{weir} was measured as difference between water level in the upstream of the weir and the V-notch weir level (see Fig. 1). The measured and calculated values of the hydraulic parameters are presented in Table 2.

Table 2

The operating hydraulic parameters

Working Scenarios	Measured parameters		Calculated parameters	
	h_{weir} (mm)	Δh (mm)	Q (L/s)	P_h (W)
S1	45	133	0.33	0.437
S2	45	81	0.33	0.266
S3	45	5	0.33	0.016
S4	45	7	0.33	0.023
S5	45	4	0.33	0.013

Table 3

Working conditions during DO measurement tests for selected scenarios

Working Scenarios / Working conditions	S1	S2	S3	S4	S5
Atmospheric pressure P_b (mbar)	1008	1002	1014	1005	1006
Water temperature (°C)	21.8	25	23.4	22.5	21.9

The working conditions during the tests of dissolved oxygen measurements for the selected scenarios are presented in Table 3.

3. Results and discussions

In order to perform data analysis, ASCE Standard recommends minimum twenty one discrete data to be selected from the continuous record of DO versus time data (reaeration curve), in each determination point, to ensure the timing criteria for the data selection so that they are representative of the reaeration curve. An example of the reaeration curve is given in Fig. 2, with the data collected for Scenario S5.

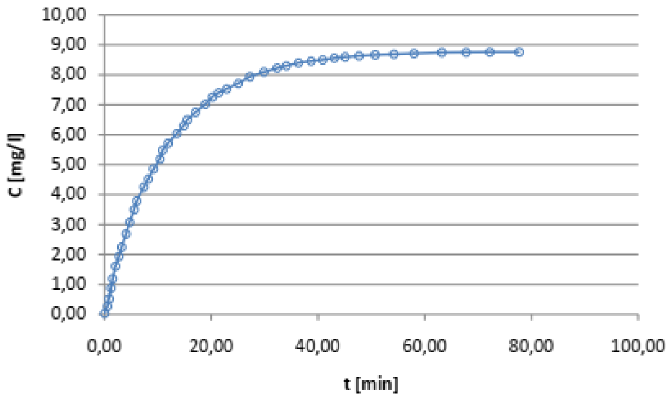

Fig. 2. DO concentration versus time data for scenario S5.

Parameter estimation procedure is performed to determine the best estimates of the model parameters in equation (2), K_La and C^*_∞, based on nonlinear regression of the DO versus time data by least-square method, using the EXCEL 2010 Solver.

The result of the test is expressed as *SOTR* (Standard Oxygen Transfer Rate) which is the oxygen transfer rate under standard conditions of pressure and temperature (meaning 101.3 kPa and 20°C).

In order to determine *SOTR*, the estimated values of K_La and C^*_∞ should be corrected to standard conditions for each determination point by the following relations:

$$K_L a_{20} = K_L a \cdot \theta^{(20-T)} \quad \text{and} \tag{5}$$

$$C^*_{\infty 20} = C^*_\infty \left(\frac{1}{\tau \cdot \Omega} \right), \tag{6}$$

where $K_L a$ and C^*_∞ represent the estimated values for the overall mass transfer coefficient and steady-state DO saturation concentration, respectively; $K_L a_{20}$ - the estimated $K_L a$ value corrected to 20 °C; θ =1.024 empirical correction factor [10];

$C^*_{\infty 20}$ - the estimated C^*_{∞} value corrected to standard conditions of pressure and temperature; τ-temperature correction factor; Ω-pressure correction factor and *T*-water temperature during test (°C).

Expression of temperature correction factor and pressure correction factor are given as:

$$\tau = \frac{C^*_{st}}{C^*_{s20}}, \quad (7)$$

$$\Omega = \frac{P_b}{P_s}, \quad (8)$$

where C^*_{st} is the DO surface saturation concentration, at the test temperature and standard pressure; C^*_{s20} - DO surface saturation concentration, at 20 °C and standard pressure; P_b - barometric pressure at test site; P_s - standard barometric pressure (101.3 kPa).

C^*_{st} and C^*_{s20} are computed using the DOTABLES [11] that generates values of DO solubility for user-specified values of water temperature, barometric pressure and salinity (for tap water the salinity is zero).

For the *i* set of measurements (point *i*) the *SOTR* value is:

$$SOTR_i = K_L a \cdot C^*_{\infty 20i} \cdot V, \quad (9)$$

where *V* represents the initial water volume in the test tank with the liquid at rest.

The average value of *SOTR* considering the *n* determination points (*n=4*) is:

$$SOTR = \frac{\sum_{i=1}^{n} SOTR_i}{n} \quad (10)$$

Standard aeration efficiency *SAE* (kg O_2/kWh) is given by:

$$SAE = \frac{SOTR}{P_h} \quad (11)$$

where P_h is the hydraulic power calculated with relation (4).

Table 4 presents the aeration parameters calculated starting from the estimated values of $K_L a$ and C^*_{∞}, corrected to standard conditions for the considered scenarios, in the determination point *i*=4.

The overall mass transfer coefficient $K_L a_{20}$, in the determination point *i*=4 (the last pool), for scenarios S1-S5 is presented in Fig. 3. One can notice that scenarios having lateral vertical slot (S3-S5) ensure $K_L a_{20}$ values superior to those having lateral submerged orifice (S1-S2) due to higher levels of turbulence.

The standard oxigen transfer rate *SOTR* and aeration efficiency *AE* of the fish ladder model for scenarios S1-S5 are presented in Fig. 4 and Fig. 5 respectively.

Table 4

Calculated values of the aeration parameters for scenarios S1-S5, in the determination point *i*=4.

Working Scenarios	K_La (h^{-1})	θ	*T* (°C)	K_La_{20} (h^{-1})	C^*_{st} (mg/L)	C^*_{s20} (mg/L)	τ
S1	4.23	1.024	21.8	4.05	8.78	9.09	0.966
S2	4.21	1.024	25	3.74	8.26	9.09	0.909
S3	4.59	1.024	23.4	4.23	8.51	9.09	0.936
S4	5.14	1.024	22.5	4.84	8.66	9.09	0.953
S5	5.26	1.024	21.9	5.02	8.76	9.09	0.964

Working Scenarios	P_b (mbar)	P_s (mbar)	Ω	C^*_∞ (mg/L)	$C^*_{\infty 20}$ (mg/L)	*V* (L)
S1	1008	1013	0.995	8.70	9.053	155
S2	1002	1013	0.989	8.04	8.754	155
S3	1014	1013	1.001	8.52	9.112	155
S4	1005	1013	0.992	8.53	8.886	155
S5	1006	1013	0.993	8.76	9.024	155

Working Scenarios	*SOTR* (kg/h)	P_h (W)	*SAE* (kg O_2/kWh)	*SAE* (mg O_2/kWh)
S1	0.0057	0.437	0.00001	13
S2	0.0051	0.266	0.00002	19
S3	0.0060	0.016	0.00036	364
S4	0.0067	0.023	0.00029	290
S5	0.0070	0.013	0.00053	535

Regarding the standard oxigen transfer rate *SOTR* for the fish ladder model the results presented in figure 4 show that, for a given type of baffle (lateral submerged orifice-S1, S2 or lateral vertical slot-S4, S5) there is no significant difference between the arrangements (in line or zigzag). The lateral vertical slot (S3-S5) ensures higher *SOTR* values than the lateral submerged orifice (S1-S2) due to higher levels of turbulence induced in the flume by the design of the baffle (the vertical slot generates local turbulence from bottom to top on both sides of the baffle, entraining more air from the water surface, compared to submerged orifice where local turbulence is created mostly at the bottom).

Regarding the aeration efficiency presented in Fig. 5 one can notice that *AE* varies significantly with the type of the baffle, in the favour of baffles with lateral vertical slot (S3-S5). In scenarios using submerged orifices (S1-S2) the head drop between pools Δh is higher than in those using vertical slot, leading to enhanced hydraulic power consumption and consequently to lower aeration efficiency.

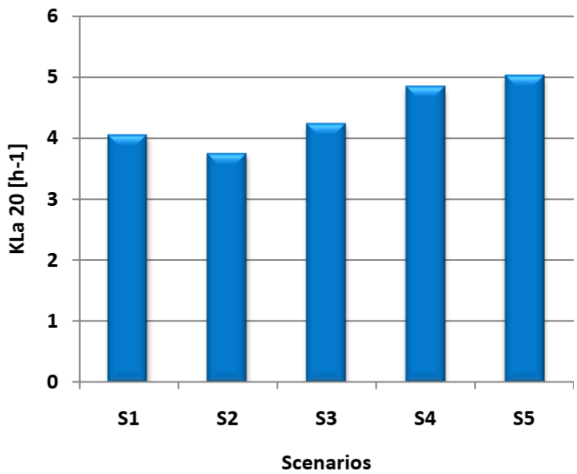

Fig. 3. Comparison of the overall mass transfer coefficient K_La_{20} for scenarios S1-S5, in the determination point i=4.

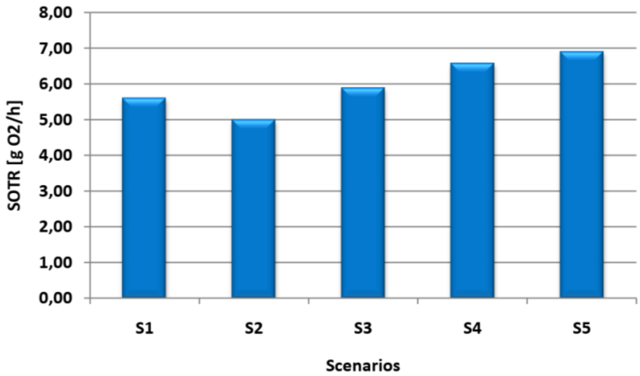

Fig. 4. Comparison of the standard oxigen transfer rate *SOTR* for scenarios S1-S5.

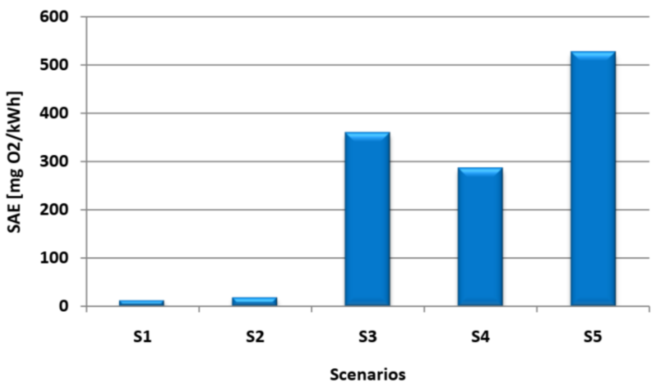

Fig. 5. Comparison of the standard aeration efficiency *SAE* for scenarios S1-S5.

As a conclusion, the best choice for designing a fish ladder model with pools and baffles, regarding both oxigen transfer rate and aeration efficiency is represented by baffles having lateral vertical slot with the arrangement in line.

6. Conclusions

The paper presents the experimental set-up, the procedure and the results obtained regarding the oxygen transfer rate and aeration efficiency of a laboratory fish ladder model. The procedure is based on a well-known standard (ASCE) applied to evaluate the *AE* of different aeration systems in tanks. The proposed procedure was developed to be applied for evaluating the *AE* in free surface flows, for a fish ladder model with baffles and pools operating in closed hydraulic circuit. Five scenarios, meaning specific type and arrangements of baffles, were considered. The present study is useful for determining the *AE* of fish ladder models in general, and represents by itself a modality for optimizing the design of fish ladder prototypes regarding the oxygen transfer.

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