A NEW AUTOMATED DEVICE FOR TURBINED WATER AERATION

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Abstract: *The paper studies a new system for air injection inside turbines draft tube, with a beneficial effect on the aquatic environment, leading to a maximum transfer of the dissolved oxygen (DO) into the discharged water with a minimum energy consumption. To achieve this goal, it is necessary to obtain an interphase contact area as large as possible, achievable by dispersing the air introduced in the discharged water as fine bubbles. In order to have a lower influence over the hydraulic circuit, and to affect as little as possible the turbine efficiency, the studied device is noninvasive. Preliminary experiments were developed using a small scale laboratory set-up regarding to solutions for water aeration in dispersed gas-liquid, turbulent and with an adverse pressure gradient flows. Finally, it is developed an automatic control system of aeration device so that it operates with a minimum energy consumption and also reaching the level of dissolved oxygen required by the user. The device will only work when there is a deficiency of oxygen in the water and will permanently ensure compliance with the water quality norms related to the dissolved oxygen content of the water in the downstream rivers of the hydro power plants (HPP).*

Keywords*: Environmental friendly turbines, turbine aeration, water quality, dissolved oxygen, automatic control system*

1. Introduction

On the international level the main energy suppliers and hydroelectric equipment manufacturers in Europe (Voith, General Electric, Andritz) and SUA (Tennessee Valley Authority) have responded to environmental concerns regarding HPP operation since 1950 and has initiated research aimed at reducing their environmental impact. Several methods for the modernization of hydraulic turbines have been implemented in this respect. The efficiency of these aeration methods from air-water oxygen transfer point of view is analyzed and compared in the literature [1], [2], highlighting the main aeration parameters: turbine geometry, air quantity, the type and place of the air intake. Although in some studies of turbine aeration systems carried out at different hydro power plants, the results were not in line with expectations, research continues because of the significant importance of aeration on ecosystems. As a consequence of these issues, HPP operators are trying to optimize the ratio of water quality improvement measures and energy efficiency.

Regarding the level of DO in hydro power plants (HPP) downstream the rivers, there are intense concerns of hydraulic turbine manufacturers and HPP users. Reduced DO content in rivers is a pollution factor, which may in some cases reach up to 0-2 mg / l DO, provided that the minimum level required for aquatic life is about 5 mgDO / l. This value varies depending on temperature / climate, pressure, organic substances, flora and fauna, which leads to the need for individual case studies.

In the United States of America (especially on the Tennessee, Saluda and Provo rivers - where real environmental disasters have been encountered), the turbines have been upgraded to respond the needs of the environment and the authorities (Water Resource Agencies) have developed [2] strategies and control systems to improve turbine performance in terms of environmental impact. During the summer months, at Deer Creek Reservoir, the DO in the discharged water from the plant was up to 0 ÷ 2 mg / l; this low oxygen value affects the fish over a distance of 3 ÷ 5 km. The criteria established by the US Environmental Protection Agency in 2006 that water has to satisfy are: minimum 3 mg / l for fish survival, an average of 6.5 mg / l for 30 days to protect the fish reproduction/development and at least 4 mg/l for cold water-sensitive invertebrates.

In Bakun, Malaysia, [3], 88% of the reservoirs contained zero DO in water deeper than 4 m (Fig. 1), and river water quality is affected up to 3-5 km in downstream of hydro power plants. In order not to affect the environment, the development of an aeration system is essential in such an area.

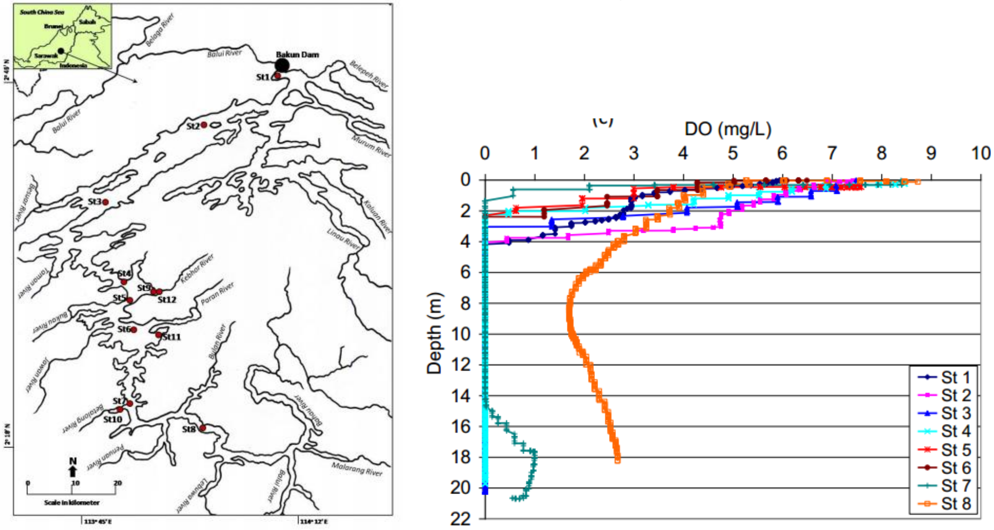


Fig. 1. Reservoirs in Bakun – Malaysia [3]

The results of water quality monitoring in Danshuei River, China [4] indicate a high concentration of phosphorus and nitrogen and reduced DO in water.

Generally, to increase the DO level by 1 mg/l, an air volume equal to 1% of the volume of flowing water is required [5]. On the other hand, in order not to affect sensitively the hydraulic performance, the air flow rate must not exceed 3% of the flow rate of the turbined water (relation 1). Current turbine water aeration methods affect the performance of hydropower on the one hand due to flow disturbance through introduction of air and on the other hand due to the energy consumption required for injection of air (e.g. a compressor station).

$$Q_{air} < (1 \div 3\%)\, Q_{water} \quad (1)$$

This is a sensitive issue for manufacturers and users of hydraulic turbines, since injecting an extra amount of air into the turbine circuit can reduce the efficiency of the turbine; therefore, air injection (mode and place of introduction, quantity, etc.) becomes important for the balance between turbine efficiency and environmental factor.

The efficiency of aeration in HPP is usually expressed by the void fraction

$$\phi = \frac{Q_{air}}{Q_{water}}, \quad (2)$$

where Q_{air} is air flow rate, respectively Q_{water} is the water flow rate. Thus, in order to increase the effect of aeration, other parameters should also be considered: air-water interface area, pressure gradient, air retention time in the water, the DO gradient upstream and downstream turbine, distribution of gas bubble size in water, and, as the case may be, the standard aeration efficiency will be calculated.

2. Laboratory study of rotational biphasic flows with adverse pressure gradient

The test bench on which the testing of rotational biphasic flows with adverse pressure gradient was conducted [6] aims at studying and testing the small-scale aeration devices, on the basis of which will be designed the aerators that can be mounted in hydraulic turbines. Emphasis is on the quality of the aeration process, respectively on the increase of the air-water interphase area, the retention time, the pressure drop on the aeration devices, their geometry and their dimensioning, etc.

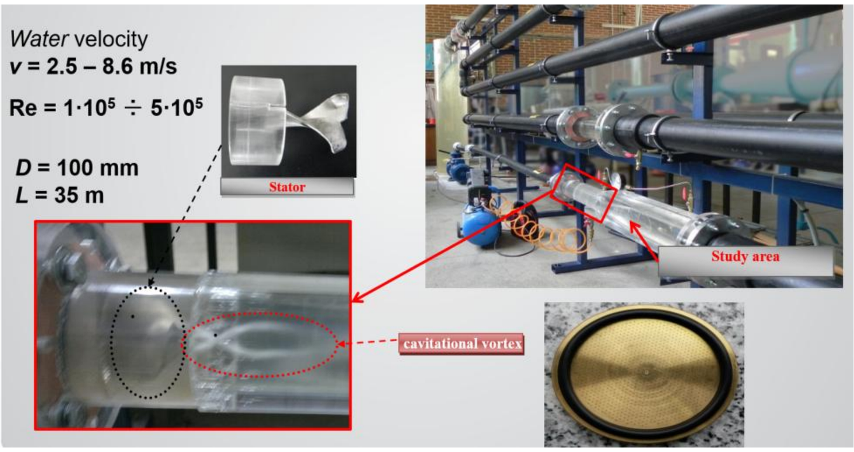


Fig. 2. Test bench for study of rotational biphasic flow with adverse pressure gradient

The test bench (Fig. 2) is made in a close loop and consists of a supply tank, from which, by means of a pump, clean water is introduced into a pipe line. The test bench is designed to simulate flow parameters in hydraulic turbines for the entire operating range of the turbine. To simulate rotational flow, the stand is provided with a transparent area, conical to the inside and parallelipipedic to the outside, made of transparent material, consisting of a stator and a divergent area. In the study area Reynolds numbers between Re = 1 10^5 ÷ 5 10^5 are covered. The study area also includes a dispersed air injection device located downstream of the stator.

The test bench is dimensioned to ensure the minimum contact time in which a particle travels from the inlet to the outlet draft tube of a Francis hydraulic turbine (at least 10 s) and an average water velocity of 3 m/s.

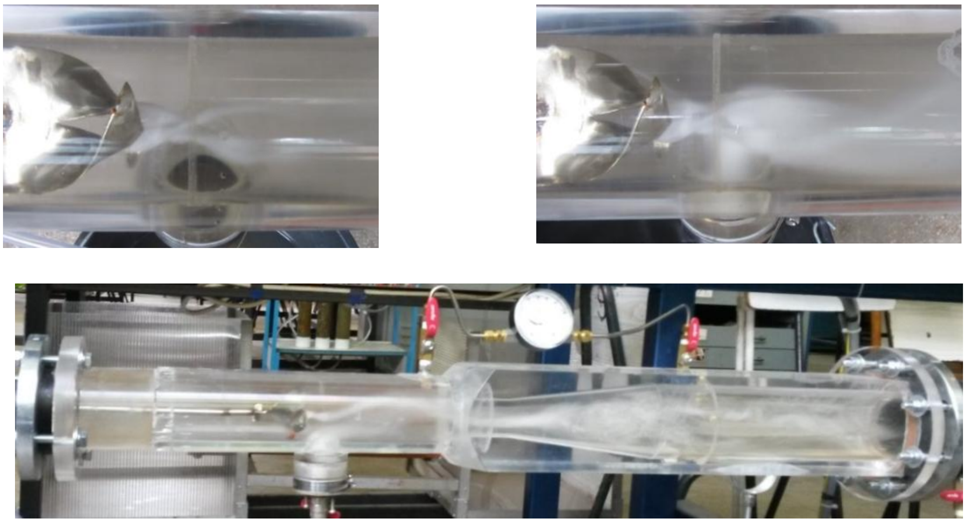


Fig. 3. Visualization area of rotational biphasic flow

With the increase of the water flow rate, the rotation impressed by the stator forms a cavitational vortex (Fig. 3). By introducing dispersed air into the study area, it is possible to study the water disperse aeration in rotational turbulent flows. Injection of the air will be controlled in accordance with the DO deficiency in the water through a non-invasive aeration device located on the pipe wall so as not to influence the flow in the hydraulic circuit. The test bench allows the study reliably of complex phenomena such as turbulent gas-liquid dispersed flows with adverse pressure gradient, where the mass transfer through the interface is a dynamic process associated with the interface dynamics and the interface area varies along the flow [7].

The test bench is equipped with a dispersing aeration device, with interchangeable plates, through which air bubbles of different sizes is injected. Thus, four perforated metal plates with orifices of 0.1mm (MP01), 0.2mm (MP02), 0.3mm (MP04) and 0.5mm (MP05) were tested under the following conditions:

- For each perforated plate, the air flow rate injected into the circuit (Q_{air} = 5, 8, 10, 12 l/min) was varied, and the water flow (Q_{water} = 1110 l / min) was kept constant
- for each perforated plate, the air flow rate injected into the circuit (Q_{air} = 5 l / min) was kept constant, and the water flow rate (Q_{water} = 330, 882, 1044, 1110 l / min) was varied.

Table 1 [8] shows the ratio between the injected air flow rate and the flow rate of water flowing through the laboratory setup, so that the relationship (1) is respected and the aeration process covers as much as possible the oxygen deficiency in the water.

Table 1: Void fraction (%) for tested MPs

Q_{water} (lpm)	MP 01				MP 02				MP 03				MP 05				Obs.
	Q_{air} (lpm)				Q_{air} (lpm)				Q_{air} (lpm)				Q_{air} (lpm)				
	5	8	10	12	5	8	10	12	5	8	10	12	5	8	10	12	
330	1.51				1.51				1.51				1.51				Non cavitational vortex
882	0.57				0.57				0.57				0.57				Incipient cavitational vortex
1044	0.48				0.48				0.48				0.48				Developed cavitational vortex
1110	0.45	0.7	0.9	1.1	0.45	0.72	0.9	1.1	0.45	0.72	0.9	1.1	0.45	0.72	0.9	1.1	Developed cavitational vortex

The entire procedure for determining standard air efficiency is described extensively in [8].

Table 2: SAE variation depending on air and water flow

Q_{water} (l/min)	MP 01				MP 05			
	Q_{air} (l/min)				Q_{air} (l/min)			
	5	8	10	12	5	8,5	10	12
330	377				408			
882	992				1017			
1044	1117				1018			
1110	1112	1797	2176	2759	1083	1826	1899	2041

Table 2 shows the standard aeration efficiency (SAE) for 0.1, respectively 0.5 mm orifices plates resulting from aeration tests.

For a better understanding of the behavior of the injected air controlled in a site hydraulic turbine, flow visualizations from the inside of the turbine were performed, in the air injection area, through the proposed demonstration model. Although the demonstration model for turbulent water aeration is not shown in this paper (existing a patent application for it), fig. 4 shows two photographic captures within the suction cone when the turbine was running at a relatively high flow rate of 57.1% and a 1% voids fraction. For this, an borescope camera with a 90° x 8 mm x 440 mm (67°) HOPKINS lens and a "Techno LED Nova 150" light source, 100 - 240 VAC, 50/60 H.

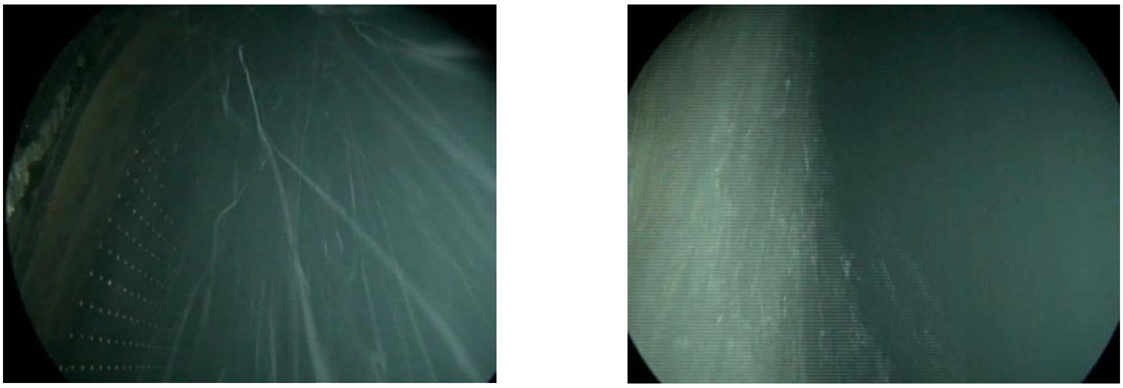


Fig. 4. Photographic captures in the injection area from a hydraulic turbine

$$f_{injection} = \frac{n}{3} \qquad (3)$$

These visualizations allowed validation of the air distribution injected inside the flow section. The injected air does not remain in the boundary layer of the wall but is distributed about one-third (out of) the draft tube section. The frequency with which air is injected in the presence of the rope vortex depends on the turbine rotational speed after the relationship (3).

Details about aeration process influence over the operation of a small hydro turbine - generator unit, are presented in [9]. The paper presents the frequency analysis of vibration signals recorded during a turbine-generator unit in operation, while different air flow rates are injected downstream the runner. From the dynamic behavior point of view, this paper show that the controlled injecting air into water downstream the runner has no negative influence over the operation of the unit.

4. Integration of the aeration device into an automated water aeration system

The automation of the aeration system discussed in this paper is required to control the air fraction injected into the hydraulic circuit, depending on dissolved oxygen in the water and the turbine operating regime. Air injection control also reduces shocks

A LabView program it was developed to help to integrate the aeration device into an automated water aeration system, by simulating the device in different operation modes. In situ measurements' results were used in simulation.

The aeration device will only work when the dissolved oxygen measured in turbined water is lower then the limit set by operator ($OD_m \geq OD_i$) to comply with river water quality regulations.

Figure 5 shows the conceptual block diagram of the automated aeration system for turbined water.

The algorithm for automatic adjustment of the oxygenation process is based on the pressure level in the draft tube cone. The algorithm follow the steps described below

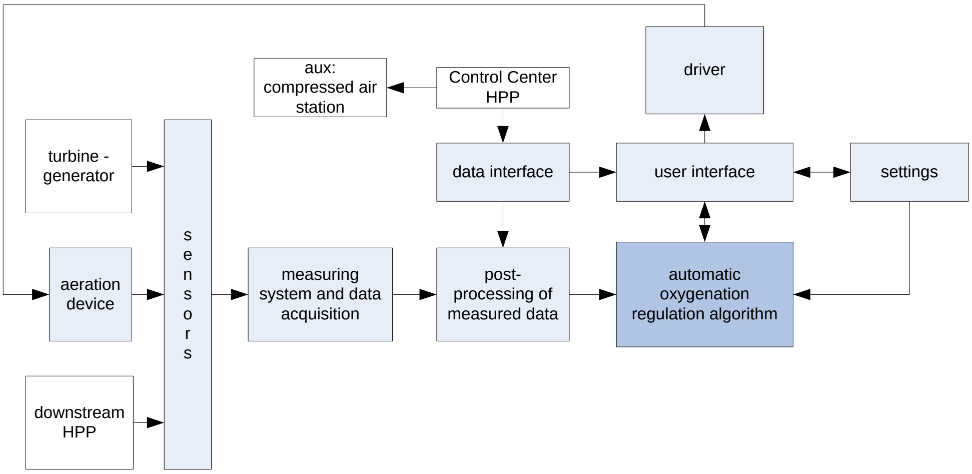


Fig. 5. Conceptual block diagram of the automated aeration system

- Air velocity at inlet after the realtion (4):

$$v=\sqrt{\frac{|dp|\cdot 2g}{\rho_{air}}}\cdot\frac{|dp|}{dp}\text{, with } dp=p_{atm}-p_{asp} \tag{4}$$

- Computes Q_{air} for different varying degrees of opening of the inlet valve, as follows

$Q_{air\ min} = Q_{water}\ \phi_{min}$
$Q_{air\ max} = Q_{water}\ \phi_{max}$
$Q_{air\ h\phi} = Q_{water}\ h_{\phi}$

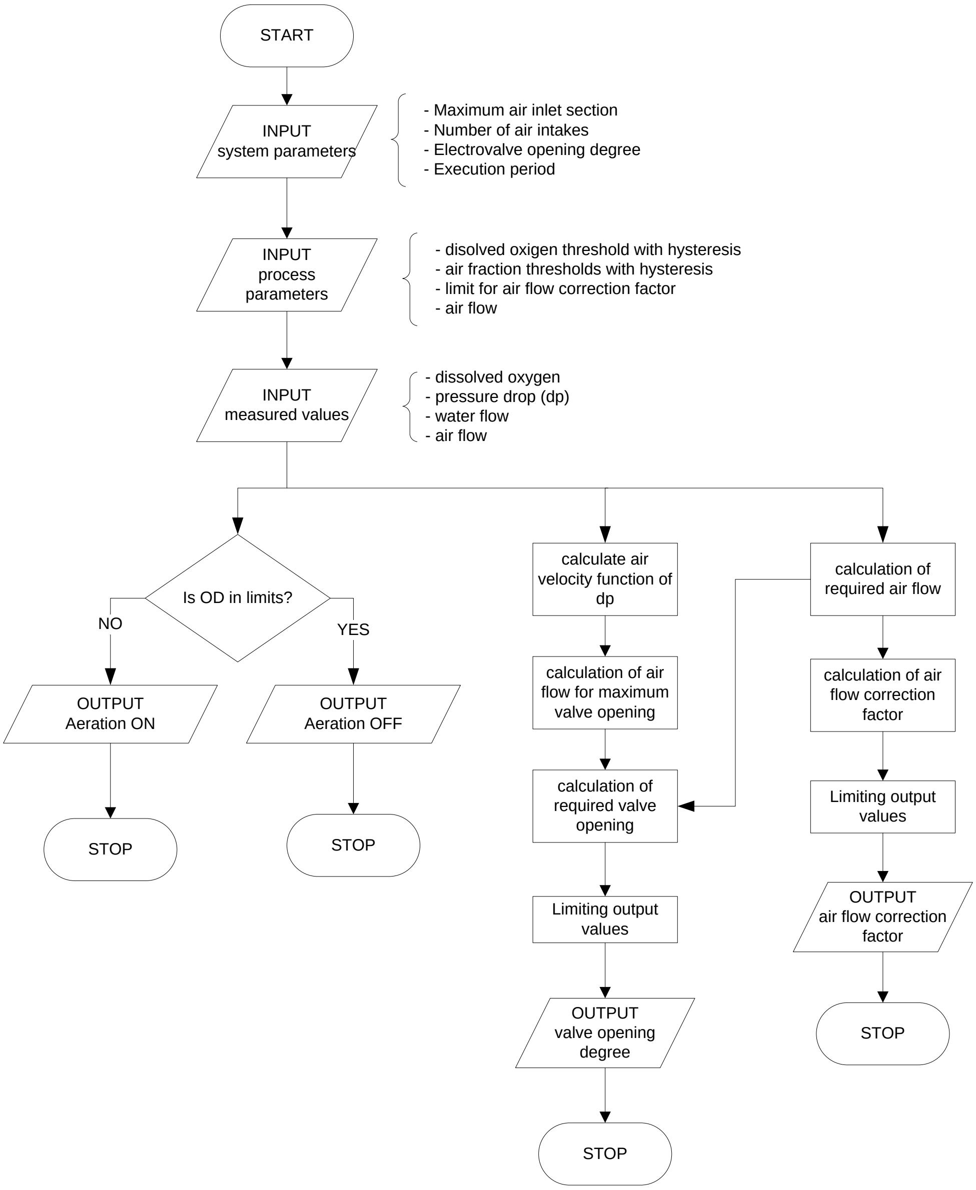


Fig. 6. Logic scheme of the algorithm for automation of the oxygenation process

The logic scheme of the automatic regulation of the aeration process is shown in Fig. 6.
Input variables:

- OD_m [mg/l] – Dissolved oxygen measured from the downstream turbine water
- p_{asp} [bar] – Relative pressure measured on the wall of the turbine CON ASPIRATOR
- Q_{water} [m^3/h] – Turbinated water flow rate

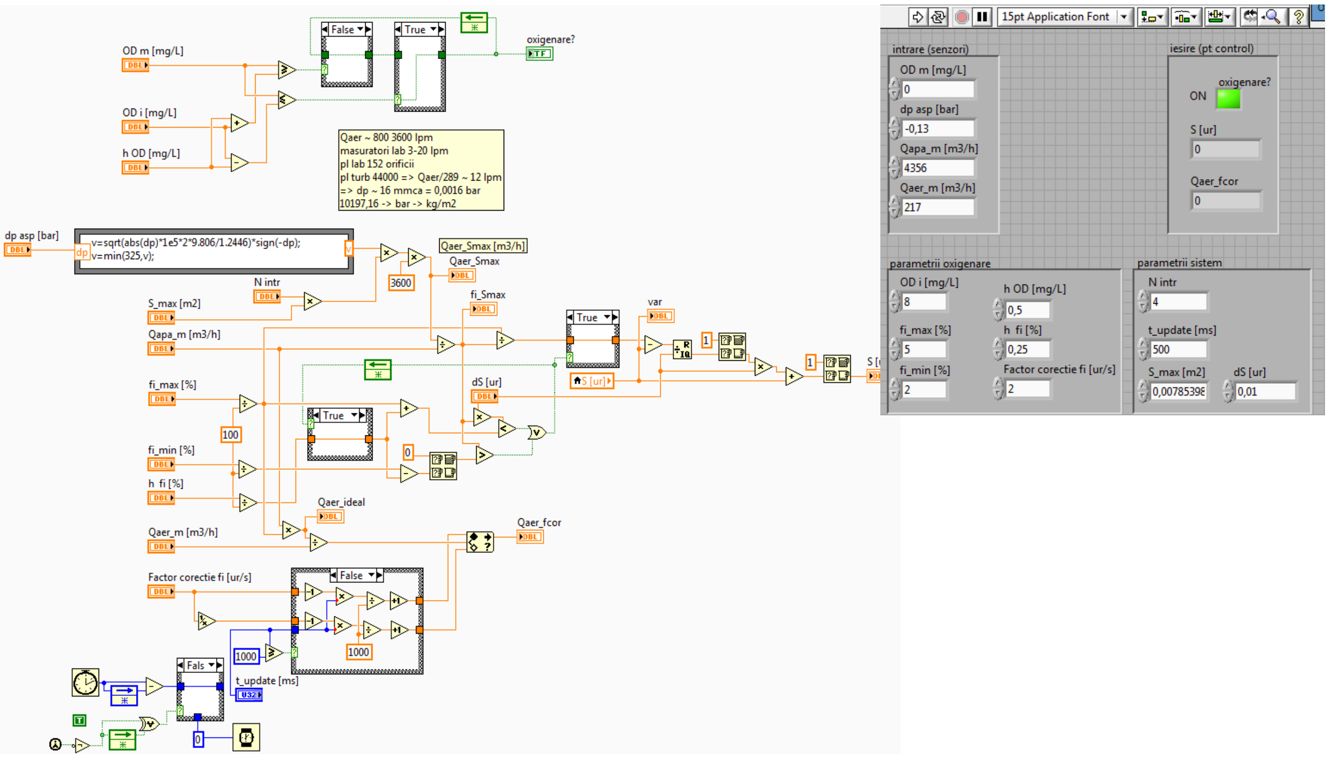
- Q_{air} [m^3/h] – Measured injected air flow rate

Output variables:

- S [ur] – opening degree of the air inlet valve
- Q_{air_fcor} – air flow rate correction factor

Parameters:

- OD_i [mg/l] – Dissolved oxygen level required downstream of HPP
- $\pm h_{OD}$ [mg/l] – hysteresis value for OD_i threshold to start/stop the aeration device
- $\phi = \dfrac{Q_{air}}{Q_{water}}$ [%] – the minimum / maximum permitted air fraction to be introduced into the hydraulic circuit
- h_ϕ [%] – hysteresis value for minimum and maximum air fraction thresholds to start/stop the aeration device
- Φ correction factor – limiting factor of the air intlet valve opening



Qaer ~ 800 3600 lpm
masuratori lab 3-20 lpm
pl lab 152 orificii
pl turb 44000 => Qaer/289 ~ 12 lpm
=> dp ~ 16 mmca = 0,0016 bar
10197,16 -> bar -> kg/m2

```
v=sqrt(abs(dp)*1e5*2*9.806/1.2446)*sign(-dp);
v=min(325,v);
```

intrare (senzori)

OD m [mg/L]: 0
dp asp [bar]: -0,13
Qapa_m [m3/h]: 4356
Qaer_m [m3/h]: 217

iesire (pt control)

oxigenare?: ON
S [ur]: 0
Qaer_fcor: 0

parametrii oxigenare

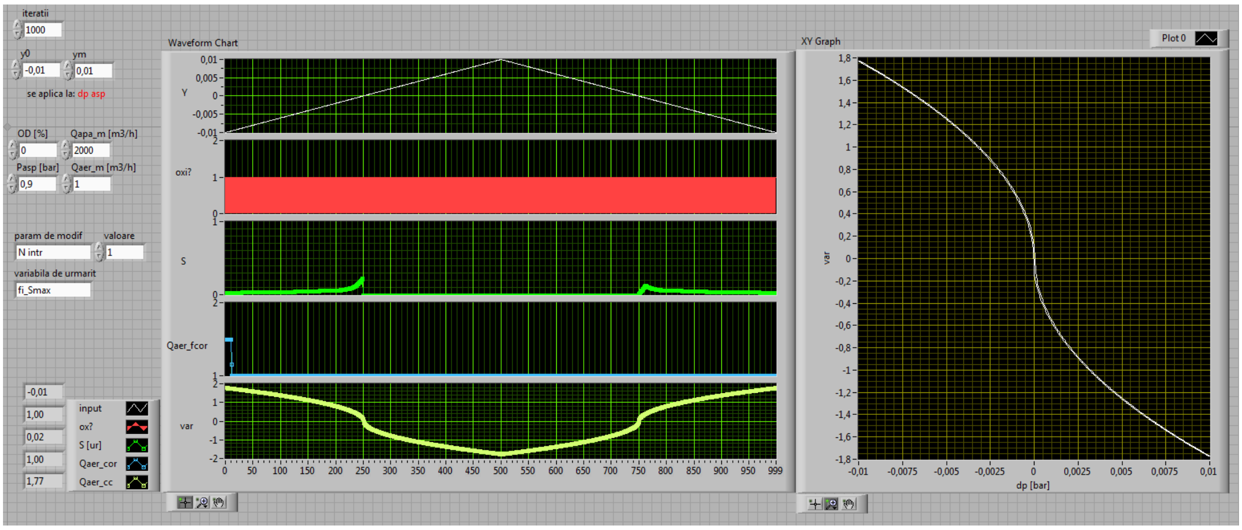
OD i [mg/L]: 8
h OD [mg/L]: 0,5
fi_max [%]: 5
h fi [%]: 0,25
fi_min [%]: 2
Factor corectie fi [ur/s]: 2

parametrii sistem

N intr: 4
t_update [ms]: 500
S_max [m2]: 0,00785398
dS [ur]: 0,01

Fig. 7. LabView implementation of the automatic aeration algorithm

In order to verify the stability of the algorithm, a test program was developed in which the input variables are automatically generated. This helps to check the limits imposed on the output variables. Figure 8 shows the pressure difference variation ($dp = p_{asp} - p_{atm}$) as well as the response of the algorithm: the valve opening degree (S) and the air flow rate correction factor (Q_{water_fcor}).



iteratii 1000

y0 -0,01 ym 0,01

se aplica la: dp asp

OD [%] 0 Qapa_m [m3/h] 2000

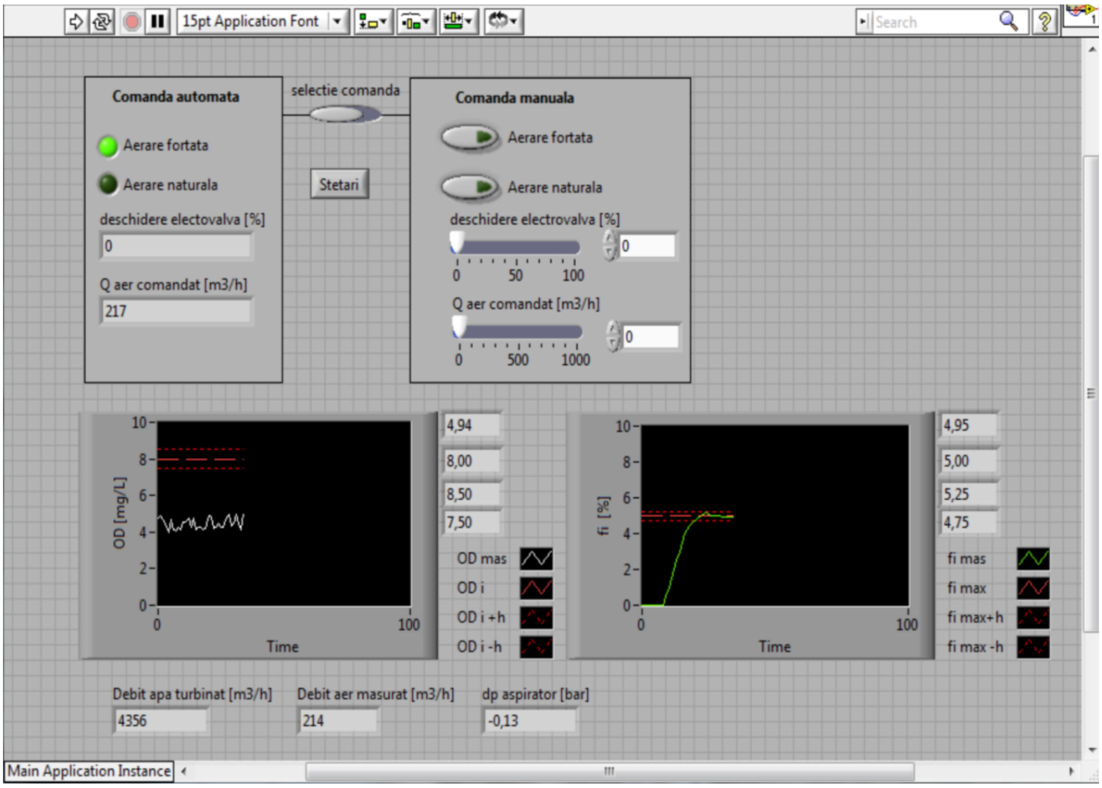
Pasp [bar] 0,9 Qaer_m [m3/h] 1

param de modif N intr valoare 1

variabila de urmarit fi_Smax

-0,01 input
1,00 ox?
0,02 S [ur]
1,00 Qaer_cor
1,77 Qaer_cc

Fig. 8. Stability check of the algorithm



Comanda automata

● Aerare fortata

● Aerare naturala

deschidere electrovalva [%] 0

Q aer comandat [m3/h] 217

selectie comanda

Stetari

Comanda manuala

Aerare fortata

Aerare naturala

deschidere electrovalva [%] 0

Q aer comandat [m3/h] 0

4,94
8,00
8,50
7,50

OD mas
OD i
OD i +h
OD i -h

4,95
5,00
5,25
4,75

fi mas
fi max
fi max+h
fi max -h

Debit apa turbinat [m3/h] 4356

Debit aer masurat [m3/h] 214

dp aspirator [bar] -0,13

Fig. 9. Graphical user interface of the automated aeration system

Figure 9 shows the graphical user interface of the automated water aeration system, which allows the operator to monitor the automatic aeration process (shown in Fig. 6), configuration of the parameters, the connection with the data communication interface and manual override of the aeration process.

5. Conclusions

Because, at the moment, there is no water aeration solution easy to implement, without damaging the energy performance and efficient from the aeration point of view, makes it difficult to comply with current legislation if the HPP water is poor in dissolved oxygen. This can lead to real ecological disasters.

In this paper is study a disperse nonintrusive aeration solution in turbulent flows corresponding with hydraulic turbines flow. Models of air injection devices are tested at reduced scale, and different void fraction ($\phi \leq$ 1-3%) are injected into the hydraulic system. For this it was developed a test bench for study of rotational biphasic flow with adverse pressure gradient where the flow parameters are in according with flow parameter from the draft tube turbine: water mean velocity, air-water contact time, rotational flow with cavitational vortex, adverse pressure gradient.

After laboratory study of the aeration devices behavior, a real scale aeration equipment is implemented and tested in situ on a Francis turbine, currently being patented and protected by copyright. Finally, an automated system for controlling the aeration device is developed, in order to operate with minimum energy consumption and to reach the level of dissolved oxygen imposed by the user. The aeration equipment works only when, in turbined water there is an oxygen deficiency, to ensure constant compliance with water quality standards, relating to the dissolved oxygen content of river water downstream of hydropower plants.

We appreciate that hydraulic turbines fitted with the proposed equipment will become *environmental friendly turbines* because it can be proven that the turbined water through them will consistently meet the ecological quality requirements

Acknowledgments

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