ASPECTS CONCERNING AERATION USING ENVIRONMENTAL FRIENDLY TURBINES

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An important concern in hydro-power generation field is represented by the quality of the water discharged from turbines, especially by the dissolved oxygen (DO) level, which jeopardize the aquatic life. Hydroturbines intakes typically withdraw water from the bottom layer, with a low DO level. Different methods for improving DO downstream the hydropower plants are used, but considering the volume of air the main parameter of the injection. The authors propose a bibliographical analysis to put in evidence the limitations of the actual methods and to prove the necessity of the optimization of the aeration process and not only the volume of injection. In order to evaluate the performances (pressure loss and mass transfer) of different aeration systems were tested: ceramic plates with uncontrolled porosity, glass plates with controlled porosity and perforated metallic plates.

Keywords: turbine aeration, dissolved oxygen, pressure loss, aeration systems.

1. Introduction

During the summer months thermal stratification of the hydroelectric dams reservoirs appears. In the surface layer, of less dense warm water, the dissolved oxygen (*DO*) level is high, while in the colder water *DO* level is low due of the organic sediments which are consuming the oxygen. When dissolved oxygen levels drop below 5.0 mg/l in water, aquatic life is put under stress. If oxygen levels remain below 1-2 mg/l for a few hours, large fish kills can occur. Hydroturbines intakes typically withdraw water from the oxygen-depleted layer, which creates the problem of low *DO* downstream the power plants. Numerous factors such as terrain, size and type of watershed, seasonal temperature variations, intensity and frequency of rainfall, amount of inflow, intake structure design, and hydropower operation affect the *DO* levels in hydropower releases.

The authors propose a bibliographical analysis of the modern methods of turbine aeration for improving the water quality downstream the hydro-power

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plants. The analysis aims to put in evidence the actual methods limitations and to prove the necessity of the aeration process optimization and not only the volume of injection. Authors performed theoretical and experimental researches concerning fine bubbles aeration in two-phase flows for different aeration devices and propose the implementation of fine bubble aeration at turbines.

2. Analyze of turbine aeration systems

The conventional methods for increasing *DO* level in hydropower releases include selective withdrawal intakes, weirs, surface pumps, diffusers, compressors and hub and draft tube baffles. All of these techniques have been tried at hydroelectric facilities, with different results concerning aeration efficiency. Testing of prototype solution has indicated that effective improvements are being achieved, improving water quality and reducing hydro’s impact on aquatic life [1]. For alternatives involving air injection or aspiration directly into the hydroturbine, about 1% of air by water volume is typically required to increase *DO* by 1 mg/l [2].

Turbine aeration is considered the most cost-effective technology for providing *DO* improvements. However, turbine aeration for improving water quality downstream the hydropower plants is often overlooked. The low *DO* problem at hydropower plants can occur when [3]: the reservoir depth is greater than 15 m, the power capacity is greater than 10 MW, the reservoir volume is greater than $61 \cdot 10^6$ m^3 and the retention time is greater than 10 days. The goal of some researches [2] was to provide up to 6 mg/l of *DO* in hydropower releases while minimizing the effect of the aeration on generating efficiency and capacity. Tennessee Valley Authority (TVA) proposed [4] a modernization program in which a series of turbines have been retrofitted in order to solve the *DO* problem.

Estimates concerning the environmental and hydraulic performance have been made in order to choose a suitable aerating turbine for a specific site. The environmental performance can be evaluated by measuring the *DO* uptake [5]

$$\Delta DO = DO_{tw} - DO_{sc} , \tag{1}$$

where DO_{tw} and DO_{sc} are the *DO* concentration in the tailwater and scrollcase. Turbine environmental performance can be determined by the aeration efficiency

$$E = \Delta DO / \left(DO_{es} - DO_{sc} \right) , \tag{2}$$

where DO_{es} is the effective saturation concentration along the path of flow [6]. The aeration efficiency is usually expressed in terms of the air void ratio $\phi = Q_a / Q_w$, with Q_a and Q_w the air flow rate and water flow rate respectively.

The hydraulic performance is measured by the effect that aeration induce in the turbine efficiency

$$\Delta\eta = \eta_a - \eta_0, \tag{3}$$

where η_a is the turbine efficiency with aeration and η_0 is the turbine efficiency without aeration.

AVT, developed by Voith Hydro and TVA, have been implemented for the first time at Norris Dam. The two ATV units contain options to aerate through the central, distributed and peripheral outlet at the exit of the turbine blades. Each aeration option has been tested in single and combined operation over a wide range of turbine flow conditions. For a single unit, with all aeration options operating, an additional *DO* uptake up to 5.5 mg/L is obtained. The amount of air aspirated was more than twice than that obtained in the original turbines with hub baffles. Depending on the operating condition and the aeration options, 0÷4% efficiency losses are obtained.

At Tims Ford Dam [7] two aeration systems have been tested – air injection into the turbine and oxygen injection through porous hoses installed in the turbine penstock to obtain a *DO* level of 6 mg/l. When operating with both systems, max. 5.2 mg/l *DO* has been obtained; when operating only with air, 4.2 mg/l *DO* has been obtained, while the *DO* upstream was 1 mg/l.

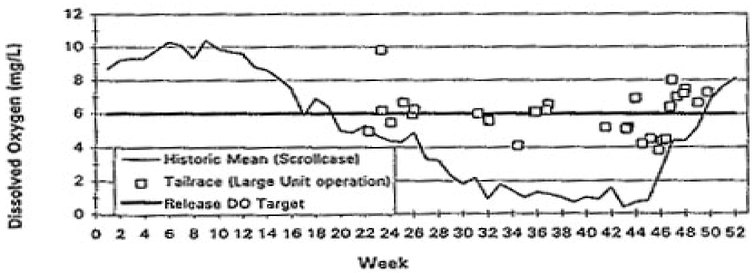

Fig. 1. Effects of aeration on DO

To complete the oxygen transfer into the discharges porous hoses have been installed in the penstock; they are fed from an on-site bulk oxygen storage facility. This system was used only when *DO* levels could not be met by operation of the air blowers alone; max. 0.3 $\mathrm{Nm^3/s}$ *OD* can be transferred into the water flow. *DO* measurements in the tailrace during the 1994 season are shown in figure 1. The data showed in all cases that the change in hydroturbine efficiency was less than 1%.

At Bull Shoals, Norfolk and Table Rock dams thrust relief openings were used since 1991 [8] for maintaining *DO* at 4 mg/l downstream the power plants. The modifications of the turbines involved installations of baffles over the thrust relief openings, adding new openings in the headcovers and modifications of air supply piping. For example, at Bull Shoals baffles have been welded onto the hub near the existing openings; the baffles were oriented to create maximum negative pressure over the opening when the turbine wicket gates were opened to produce maximum turbine efficiency. At Table Rock a baffle ring was added upstream the hub and the existing openings have been enlarged.

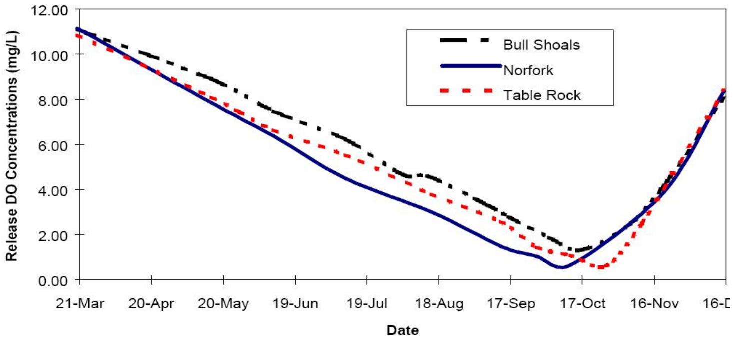

Fig. 2. Mean Annual Dissolved Oxygen Variations at Bull Shoals, Norfork and Table Rock Dams [8]

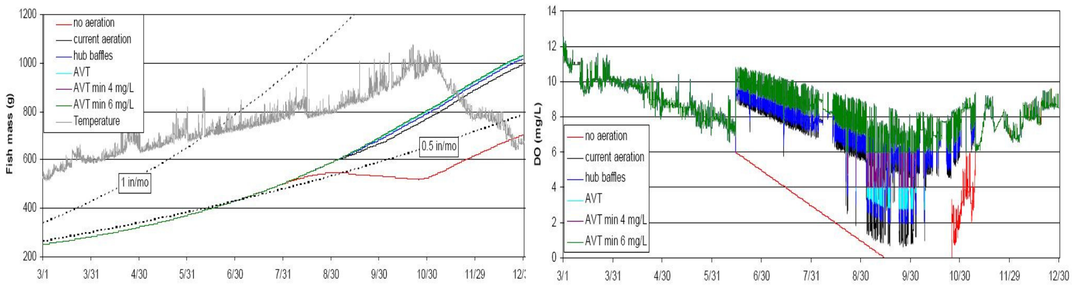

Fig. 3. The results of the model with different aeration scenarios for 1996 (moderate wet year)

Tests on a model Francis turbine were also performed by Papillon [9]. The different tested devices included 3 types of runner cone venting and peripheral aeration by the discharge ring. Studies and analyzes concerning *OD*, temperature and fish growth have been performed [8] for each month, downstream the power plant situated on the Saluda River. Based on historical data from 1990-2005 a model for setting the site-specific standard for *DO* have been developed (fig. 3). Latest Environmental Protection Agency trout-water criteria for 2006 are: for survival of trout – min. 3 mg/l, for growth protection – 6.5 mg/l for an average of 30 days, for sensitive cold-water invertebrates – min. 4 mg/l.

Air would be injected [10], [11] into the draft tube through existing passages (vacuum breaker systems and snorkel tubes of the two turbines using air compressors, fig. 4) to produce a mixed air-water flow that would raise *DO* concentrations. This concentration, in the releases from the reservoir, during the late summer months is about 0÷2 mg/l; these low values have impact on fish on about 3÷5 km. The new turbine aeration system improved *DO* with 3.5 mg/l.

For each test the aeration efficiency was calculated as follows

$$E = (C_d - C_0)/(C_s - C_0), \tag{4}$$

where C_0, C_d are *DO* concentration upstream and downstream respectively, C_s is the *DO* saturation concentration at water surface.

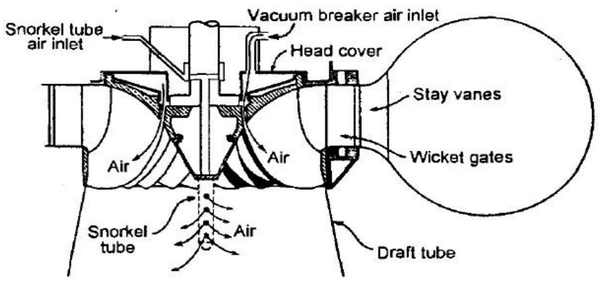

Fig. 4. Aeration through vacuum breaker system and snorkel tube

For this site the turbine aeration performance can be improved through the installation of hub baffles and/or blowers to allow forced air injection into the turbines [12].

In Romania, although the quality of the river water is a present issue, presenting interest both for the energy producers and for the inhabitants from the areas situated downstream the hydraulic power plants as well, aren't made investments in the power plants rehabilitation from the aeration point of view. There are ongoing rehabilitation projects, but none of them involve yet the water quality and especially *DO*. Air induction systems have been already implemented, but for diminishing the central vortex (at partial load); these systems are not efficient for aeration.

3. Influence of air injection on oxygen transfer

The author's researches showed that, in mass transfer processes, not the quantity of air injected is important but the quality of the injection, meaning bubbles size, pressure loss on the aeration device etc.
Considering a porous or a perforated plate immerged at the *H* depth into a basin with water. From the equilibrium of surface tension force and upward Archimedean force, neglecting the air weight from bubble,

$$\rho g (4/3)\pi R_0^3 = 2\pi r_0 \sigma \ , \tag{5}$$

results the initial radius of gas bubble

$$R_0 = \left(\frac{3}{2} \cdot \frac{r_0 \sigma}{\rho g} \right)^{1/3}, \tag{6}$$

where r_0 represents the capillary tube radius, σ – the gas-liquid coefficient of surface tension, ρ_l – liquid density. As the size of the orifices directly affects the initial radius of the bubbles and the pressure needed for their formation, different types of fine bubble aeration systems have been tested and compared [13].

The pressure loss on different aeration systems (circular plates Φ 40), made from a variety of materials, have been tested at a hydrostatic head H=0.9 m:

- ceramic porous plate (CP) with a volumetric porosity of 40 ÷ 50% and a thickness of 14 mm, made of sintered powder of crystallites, disposed in irregular arrangements, which forms pores with different shapes and sizes;
- glass plates (GP) of 9 mm thickness with porosity in the ranges 0.1 ÷ 0.25 mm and 0.25 ÷ 0.315 mm, made from glass particles of known sizes, thus issuing a controlled porosity;
- metallic perforated plates (MP) with different diameters of the orifices: d = 0.5 and 1.6; in order to neglect the contraction coefficient of the orifice the plates were made following the condition $l = 5d$, where l is the length of the orifice.

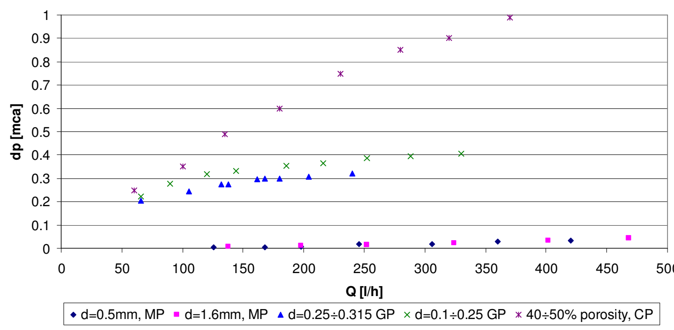

Fig. 5. $\Delta p = f(Q)$ variation for all the plates tested

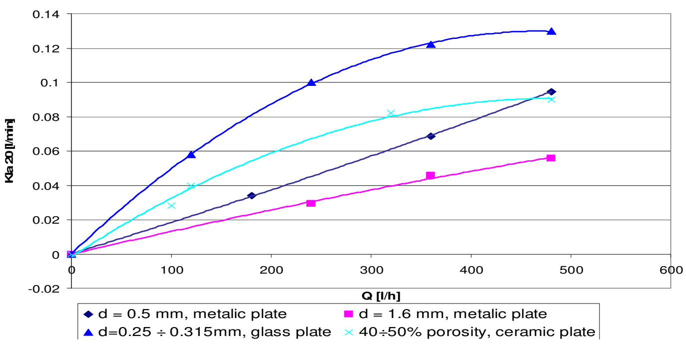

Fig. 6. $Kla_{20} = f(Q)$ variation in standard conditions

From all the aeration systems which have been tested, the metallic plates have the smallest pressure loss – about 10 times smaller than GP and even more for CP.

The experiments concerning the aeration performance have been performed in accordance with the standard for measuring the mass transfer in clean water [14], in a rectangular tank filled with 90 l of tap water. For all the tested plates the temperature and pressure correction have been accomplished, thus resulting the volumetric mass transfer coefficient at 20 ºC.

As shown in figure 6, for air flow rates in the range 0 ÷ 480 l/h the glass plates and the ceramic plates have a better mass transfer than the metallic plates. Also, the Kla values for the ceramic and glass plates have the tendency of reaching constant values, while the Kla values for the metallic plates have an increasing tendency. Authors estimate that at higher air flow rates than the ones used in these measurements, the volumetric mass transfer coefficient is improving.

4. Conclusions

Extensive researches have been made in order to validate aerating concepts and determine key parameters affecting aeration performance. Multiple methods for improving *DO* downstream the power plants have already been tested: upgrading existent aeration systems, developing new aeration systems, combinations of these or even replacing air with oxygen injected inside the penstock. Some turbine component geometries have been developed in order to efficiently draw air into the turbine as a natural consequence of the design and for minimizing power lost as a consequence of aeration.

As the air injection is limited at 1÷3% of the turbine flow rate (to limit the energetic losses), it is not enough for a good aeration (target value: 5÷6 mg/l *OD*).

Although in some studies concerning turbine aeration systems, at different power plants, the overall results were not as good as expected (e.g. Wahl and Young, 1995), the researches continue due to the significant importance that aeration has upon ecosystems and to the regulations regarding water quality. As a consequence the hydro operators try to balance environmental responsibility and economical power generation.

Authors outline that the size of the orifice affects both the initial radius of the bubbles and the pressure needed for their formation, as well as the mass transfer. The performances regarding the mass transfer and the pressure loss have been determined for the following plates: ceramic, glass (porosity 0.25 ÷ 0.315) and metallic (diameter of the orifices of 0.5 mm and 1.6 mm).

For future developments efforts are needed in order to optimize the *DO* transfer. The air admission without affecting the energetic performances is limited and is not enough for obtaining the desired level of *DO* downstream the power plants. Thus, the quality of the injection, in terms of *DO* transfer optimization, is the way to improve the global ecologic balance without affecting the energetic balance.

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