

PATRYK WÓJTOWICZ¹, MAŁGORZATA SZLACHTA¹, ANDRZEJ KOTOWSKI¹

MEASUREMENT OF AIR–WATER OXYGEN TRANSFER OF CYLINDRICAL VORTEX FLOW REGULATORS AT A RECIRCULATING SYSTEM

Hydrodynamic flow regulators are used for diversion and/or limiting excess discharge in wastewater and stormwater systems as a replacement for traditional flow throttling devices. They are highly efficient, reliable and free from common disadvantages of traditional devices. Recent research of the authors indicated that atomization of a liquid by vortex flow regulators accelerates oxygenation and prevents the putrefaction process in wastewater and storm water collection systems. The study presents experimental results of the oxygen transfer measurements for basic designs of cylindrical hydrodynamic flow regulators in a closed-circuit experimental setup at the semi-commercial scale. The oxygen mass transfer coefficient, standard oxygen transfer rate and standard aeration efficiency were determined for the range of tested configurations by the clean water test.

1. INTRODUCTION

Flow regulation devices are usually placed in remote locations and in harsh environments where inspection and regular maintenance are difficult and costly. However, such devices are important components of the system; thus, in most cases their failure can cause severe damage. Hydrodynamic or vortex flow regulators are robust and cost-effective alternatives to traditional throttling devices that are commonly used in engineering. These conventional devices include throttling pipes, orifice plates, penstocks, and valves of various kinds and designs such as balances and float or baffle flow regulators [1]. All of these devices control flow by reducing the cross-section by means of mechanical or electric controls which lowers their reliability. Furthermore, free flow area reduction may prevent the passage of debris resulting in blockages. Vortex regulators are extremely efficient, reliable and free from these disadvantages [2–5].

¹Faculty of Environmental Engineering, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland; corresponding author P. Wójtowicz, e-mail: patryk.wojtowicz@pwr.wroc.pl

It is well known that dissolved oxygen deficiencies can be problematic in natural waters and in sewage systems [6–9]. Therefore, it is important to restore the oxygen balance with effective and inexpensive methods and devices [10–12]. Recent research of the authors indicated that the atomization of a liquid by vortex flow regulators accelerates oxygenation and prevents the putrefaction process in wastewater and storm water collection systems [13]. To date there has been no systematic research available in the literature regarding the aeration efficiency of vortex flow regulators.

This paper investigates the aeration efficiency of semi-commercial scale hydrodynamic flow regulators in order to determine their application potential in environmental engineering. In laboratory experiments, different device geometries of hydrodynamic flow regulators were investigated for a range of flow rates.

2. MATERIALS AND METHODS

Figure 1 provides the details of the cylindrical vortex regulator used in testing. The basic device is composed of three main elements: a short inlet pipe (having a diameter d_{in}), vortex chamber (having a diameter D and height h_c) and the outlet (d_{out}) placed in the centre of the bottom plate. The liquid flows into the chamber through a tangential inlet that imposes vortical motion which is then sustained until the outlet is reached. An air core is formed in the centre (having a diameter d_a) blocking the effective cross-section of the outlet. When the flow rate is low, the resistance is minimal and liquid passes with minimal losses; however, when the water head at the inlet increases, the vortex motion becomes stronger intensifying the throttling effect.

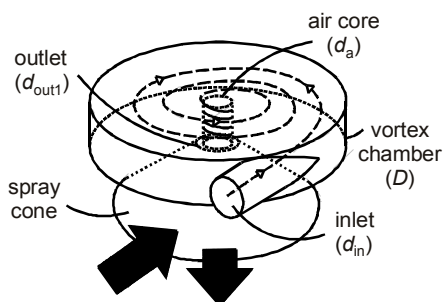


Fig. 1. Schematics of a cylindrical hydraulic flow regulator

Discharged liquid leaves the outflow orifice in the form of a hollow spray cone. The shape and form of the liquid sheet emanating from the vortex flow regulator is dependent on the pressure head and flow rate. For relatively low pressures (ΔH approximately equal to the vortex chamber height) an *onion* stage of spray atomization was observed. For practically relevant pressure drops, the devices operated in *tulip* or *full atomization* stage [14, 15].

The basic design of vortex regulators utilizes only the bottom outlet (Fig. 1) for discharging liquid from the vortex chamber. In this configuration, they are optimized for flow throttling purposes. It is possible to use regulators in two other modes of operation: discharging from a single upper outlet or two outlets (upper and lower) at the same time. Results of research including these two new modes of operation will be reported in forthcoming papers.

Semi-commercial scale models of hydrodynamic flow regulators were tested in a recirculating system. The experimental setup consisted of a feed tank equipped with a circulation pump, an upper tank and a supply system where the models were mounted. The flow rate (q_v , dm³/s) and pressure drop (Δp , kPa) were continuously recorded while the air core diameter (d_a , mm) and spray cone angle (γ , deg) were determined from photographs.

The absorption tests were performed in compliance with the unsteady state clean water test procedure [16–18] in a recirculating system. The rate of oxygen transfer across an air–water interface can be described with a general transport equation based on Fick's first law [19, 20]:

$$V \frac{\partial C}{\partial t} = KA \left(\frac{p_a}{H} - C \right) \quad (1)$$

where: C – oxygen concentration in water, kmol/m³, V – volume over which C and A are measured, m³, t – time, s, A – gas–liquid surface area contained in the volume V , m², p_a – partial pressure of oxygen in the air, Pa, H – Henry's law constant, m³·Pa/kmol, K – the bulk mass transfer coefficient, m/s.

The final form was obtained using the Lewis and Whitman [21, 22] gas transfer model (stagnant two-film model) and ignoring resistance from a gas film (which is valid for oxygen due to its low solubility in water):

$$\frac{dC}{dt} = K_L a_{(T)} (C_{\text{sat}} - C) \quad (2)$$

where: $K_L a_{(T)}$ – the overall volumetric oxygen transfer (liquid phase) coefficient at test temperature (T , °C), h⁻¹, $C_{\text{sat}} - p_a/H$ is the saturation concentration of dissolved oxygen, mg O₂/dm³.

For fitting the experimental data, the integrated formula was used:

$$C = C_{\text{sat}} - (C_{\text{sat}} - C_0) \exp(-tK_L a_{(T)}) \quad (3)$$

The overall oxygen transfer coefficient $K_L a_{(T)}$ was estimated using Eq. (3), and subsequently adjusted to standard conditions (20 °C, 101.325 kPa). The standard oxy-

gen transfer coefficient $K_L a_{(20)}$ (h^{-1}) was then used to determine values of the standard oxygen transfer rate SOTR ($\text{kg O}_2/\text{h}$) and standard aeration efficiency SAE ($\text{kg O}_2/\text{kWh}$).

Tap water in the system was deoxygenated with the use of sodium sulphite catalysed by cobalt chloride. The dissolved oxygen concentration in the system (C) was monitored with two Hach LDO probes at upstream and downstream locations. The total dissolved solids (TDS) concentration was monitored by a WTW TetraCon 325 electrical conductivity probe. Differential pressure was measured with Aplisens APC-2000ALW pressure transducers connected to a PMS-100R data logger. Flow rate was measured using an Endress Hauser Promag 53W electromagnetic flow meter and the data recorder Memograph M RSG40. Barometric pressure as well as water and ambient air temperature were constantly recorded during the experiments.

A total of 35 experimental runs were carried out and 8 different geometrical constructions were examined. Tested inlet and outlet diameters ranged between 30 and 80 mm for a vortex chamber diameter of 290 mm. Each individual device was tested for a range of flow rates, from minimum to maximum throughput limited by the maximum operating pressure head. The flow rate was varied between 0.61 and 7.43 dm^3/s while the pressure drop was in the range of 8.2–48.8 kPa. Corresponding pressure head (in meters of water) was between 0.84 m and 4.98 m.

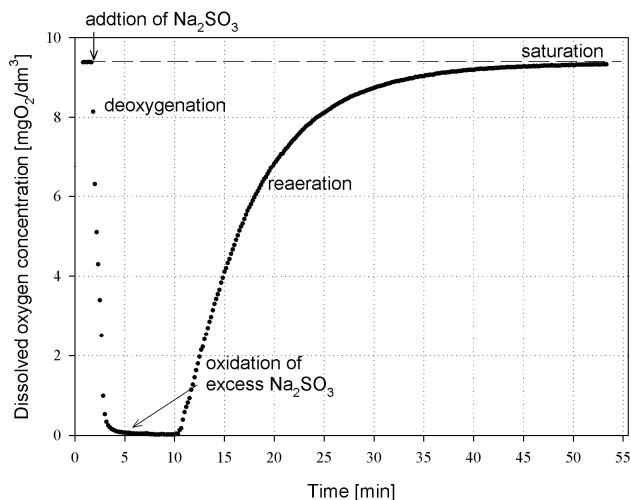


Fig. 2. Sample of the experimental results obtained during the absorption test showing the variation of the DO concentration over time

Figure 2 presents a typical time profile of the dissolved oxygen concentration obtained in this study for a cylindrical vortex flow regulator. In this figure, all stages of an unsteady clean water test can be observed (deoxygenation–reaeration–saturation).

3. RESULTS AND DISCUSSION

3.1. EFFECT OF HYDRAULIC AND GEOMETRICAL PARAMETERS ON THE OXYGEN TRANSFER COEFFICIENT

Figure 3 illustrates the effect of flow rate on the overall oxygen transfer coefficient $K_L a_{(20)}$ for cylindrical hydrodynamic flow regulators. The presented data were obtained for various geometrical configurations. For regulators with a single lower outlet, the obtained values of $K_L a_{(20)}$ ranged between 2.62 h^{-1} and 15.57 h^{-1} for the flow rates of $0.61 \text{ dm}^3/\text{s}$ and $7.43 \text{ dm}^3/\text{s}$, accordingly. Standard oxygen transfer rates values were in the range of $53\text{--}316 \text{ g O}_2/\text{h}$.

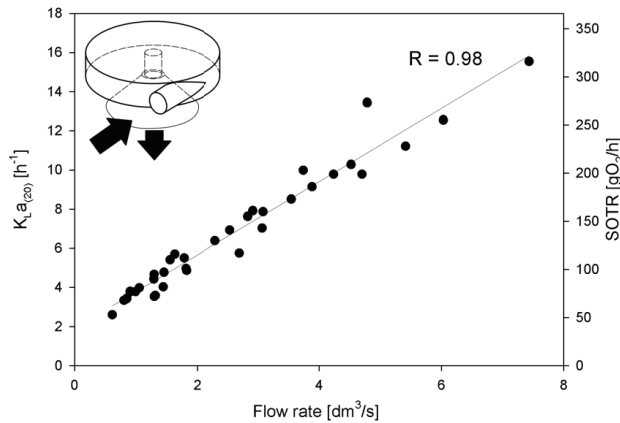


Fig. 3. Effect of the flow rate on the standard oxygen transfer coefficient and standard oxygen transfer rate for hydrodynamic flow regulators

The oxygenation performance of vortex flow regulators was determined to be dependent on the flow rate, geometrical parameters as well as on number and arrangement of active outlets with these parameters in general influencing atomization quality. Hydrodynamic flow regulators transfer atmospheric oxygen to water mainly by creating a gas–liquid interface by means of atomization. The regulator produces the hollow cone water spray at the outlet with most of the drops concentrated at the outer edge of the conical spray pattern. Additional effects are introduced when the water jet discharged from the regulator hits the downstream pool at high speed resulting in the entrainment of air.

The overall volumetric oxygen transfer coefficient is proportional to the flow rate with a good fit obtained for the linear model and the experimental data. The increase in the volumetric oxygen transfer coefficient together with the flow rate can be explained by an increase of the surface renewal rate for mass transfer. The slope of the linear function is not constant among the tested devices which can be explained by the effect of geometrical parameters.

To describe the effect of geometrical parameters on aeration efficiency of hydrodynamic flow regulators, the geometrical constant K was introduced [2]. This dimensionless parameter incorporates essential geometrical parameters as inlet, outlet and vortex chamber radii (r_{in} and r_{out} , respectively) as well as the inlet swirl radius ($R_0 = D/2 + d_{in}/2$):

$$K = \frac{R_0 r_{in}^2}{r_{out}^3} \quad (4)$$

The plotted curve based on 34 runs was fitted with a mathematical function using non-linear multiple regression for the best least-squares estimation to the experimental data. After statistical analysis using the software Statsoft Statistica, the following parameters were included in the final form of the formula: flow rate, pressure head and the geometrical constant of the vortex flow regulator:

$$K_L a_{(20)} = 1.87q_v + 0.0279K + \Delta H^{0.5} h^{-1} \quad (5)$$

All parameter estimates are significant at the $\alpha = 0.05$ level for the sum of squares for the error $SSE = 4.46$ and correlation coefficient $R = 0.99$. Equation (5) is valid for the following ranges of parameters $0.46 \leq K \leq 22.2$, $0.61 \text{ dm}^3/\text{s} \leq q_v \leq 7.43 \text{ dm}^3/\text{s}$; $0.84 \text{ m} \leq \Delta H \leq 4.98 \text{ m}$. In the empirical formula, Eq. (5), the flow rate is given in dm^3/s and the pressure head in metres of water column. The plot of the predicted values with Eq. (5) against the experimental data is given in Fig. 4.

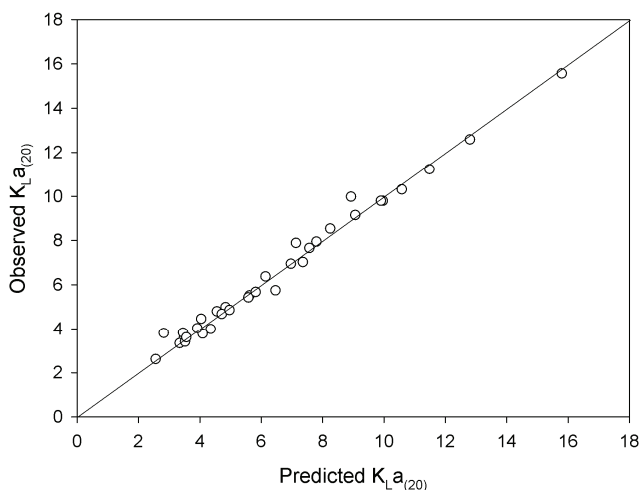


Fig. 4. Observed versus predicted values of the standard oxygen transfer coefficient $K_L a_{(20)}$ based on Eq. (5)

The derived empirical relationship is of practical significance as it can be used to determine the oxygen transfer rate at the range of flow rates tested. However, care must be taken when using this formula in field conditions as the effect of scale on the mass transport of oxygen to water for vortex regulators is still under investigation. The relationships derived for semi-commercial scale models must first be tested to verify their limits when scaled up.

3.2. EFFECT OF HYDRAULIC AND GEOMETRICAL PARAMETERS ON THE STANDARD AERATION EFFICIENCY

Pressure drop was found to better describe relationship between the regulator performance and standard aeration efficiency than the flow rate does. The effect of pressure head on standard aeration efficiency SAE is shown in Fig. 5 for cylindrical flow regulators.

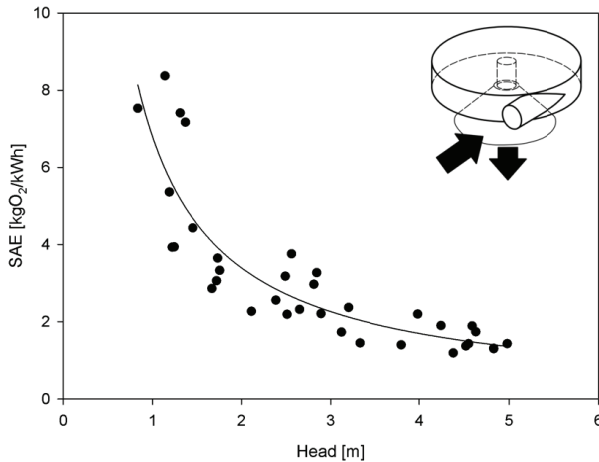


Fig. 5. Standard aeration efficiency (SAE) vs. pressure head for the tested cylindrical flow regulators

The study of the relationship between standard aeration efficiency and pressure head of vortex flow regulators indicated that they were best described by a power function model. Generally, for increasing values of pressure head ΔH , the values of SAE were decreasing. However, the most significant drop in the SAE value was observed up to 3.0 m, beyond this boundary value of the SAE was approaching a constant value of about 1.5 kg O₂/kWh. Vortex regulators are most efficient for a low pressure drops.

For the practically important pressure heads – up to 3.0 m (common pressure head we have at disposal in storage tanks or weirs [1]), values of SAE varied between approx. 2.0 kg O₂/kWh and 8.0 kg O₂/kWh.

Aeration by hydrodynamic flow regulator is similar to spray aeration (upward- and downward-directed) but not prone to blockages and with lower requirement for pressure head to drive the atomisation. Vortex regulators perform very well comparing to devices used specifically for aeration in environmental engineering. The oxygen transfer coefficients range from 0.12 h^{-1} for coarse bubble diffusers to 40.15 h^{-1} for very fine bubble diffusers obtained by Schierholz et al. [23].

4. SUMMARY

It has been demonstrated that hydrodynamic flow regulators can be used as both throttling and reaeration devices in urban storm as well as wastewater systems. Vortex regulators are not prone to blockages and have lower requirement for pressure head.

The overall oxygen transfer coefficient for the tested vortex regulators is proportional to the flow rate and atomization quality. The standard aeration efficiency of flow regulators is inversely proportional to pressure head.

The derived empirical relationship between $K_L a_{(20)}$ and major hydraulic and geometrical parameters is of practical significance and it can be used to determine the oxygen transfer rate at a range of tested flow rates. The effect of scale and performance under real installation conditions must still be studied.

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