

Research on the Aeration Systems' Efficiency of a Lab-Scale Wastewater Treatment Plant

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Abstract—In order to obtain efficient pollutants removal in small-scale wastewater treatment plants, uniform water flow has to be achieved. The experimental setup, designed for treating high-load wastewater (leachate), consists of two aerobic biological reactors and a lamellar settler. Both biological tanks were aerated by using three different types of aeration systems - perforated pipes, membrane air diffusers and tube ceramic diffusers. The possibility of homogenizing the water mass with each of the air diffusion systems was evaluated comparatively. The oxygen concentration was determined by optical sensors with data logging. The experimental data was analyzed comparatively for all three different air dispersion systems aiming to identify the oxygen concentration variation during different operational conditions. The Oxygenation Capacity was calculated for each of the three systems and used as performance and selection parameter. The global mass transfer coefficients were also evaluated as important tools in designing the aeration system. Even though using the tubular porous diffusers leads to higher oxygen concentration compared to the perforated pipe system (which provides medium-sized bubbles in the aqueous solution), it doesn't achieve the threshold limit of 80% oxygen saturation in less than 30 minutes. The study has shown that the optimal solution for the studied configuration was the radial air diffusers which ensure an oxygen saturation of 80% in 20 minutes. An increment of the values was identified when the air flow was increased.

Keywords—Flow, aeration, bioreactor, oxygen concentration.

I. INTRODUCTION

IN order to carry out the biological processes, the aerobic bacteria require oxygen, either in the conventional and innovative processes for organic matter and nitrogen removal [1], [2]. Oxygen can be introduced in the water body by coarse, medium or fine bubble dispersion systems, each of them having its own efficiency [3], [4].

In most wastewater treatment plants the biological processes are aerobic ones and they require large oxygen quantities, thus being high energy consumers [5]. Due to the high energy costs, solutions for biological processes costs reduction are permanently searched and increasing the oxygenation efficiency is one of them [6]-[8]. Another

important factor in the decision making process to choose the proper aeration system is the long term cost, considering investment and operational costs. Equipment that provides high aeration efficiency usually might have high investment costs, but if it is considered decreasing of the power consumption, the balance results positive if compared to using low-efficiency equipment, that have lower investment costs [9].

Aerobic biological treatment rely on interfacial gas transfer, with a gas-liquid interface created by either shearing the liquid surface with a mixer or turbine, or by releasing air through spargers or porous materials [4].

The most frequently used aeration systems in wastewater treatment plants are pneumatic ones – mainly consisting of a blower or compressor and different air dispersion systems [3]. The dispersion systems influence considerably the quantity of oxygen transferred into the water mass by the air bubble. The main air dispersion systems used in wastewater treatment plants were perforated pipes, membrane and ceramic diffusers being the most often installed [10].

Using the fine bubbles air diffusers increases the specific air-water contact surface and thus increases the mass transfer of oxygen from air into the water.

The paper presents the results obtained for oxygen mass transfer using three different types of air dispersion systems, on a pilot plant designed for leachate treatment.

Methods for evaluating aeration systems may be both theoretical and experimental [11], [12]. In the current study experimental research results are presented

Testing the aeration systems in biological reactors, both as geometric location and as aeration performance, has the aim of evaluating global oxygenation capacity as well as assuring a high homogenization in the bioreactors.

Obtaining uniform oxygen concentration and complete mixing conditions in bioreactors is essential for obtaining high efficiency processes.

Experimental research, although time and resources consuming when compared to simulations, are necessary for obtaining the data for calibrating and validating theoretical models that can provide tailored solution for different known situations [13].

II. MATERIALS AND METHODS

The experimental tests were conducted at University Politehnica of Bucharest, in the Dynamics of Multiphase Fluids Flow Laboratory. The laboratory has a pilot leachate treatment plant equipped with porous diffusers, membrane

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diffusers and perforated pipes aeration systems.

The pilot installation is composed of two aerobic biological tanks (bioreactors) and a lamellar clarifier. The first aerobic tank has a volume of 0.610 m³, with aeration system consisting of two perforated pipes and two tubular porous diffusers (Fig. 1). The second aerobic tank has a volume of 0.610 m³ and aeration system consisting of two disc membrane diffusers (Fig. 1).

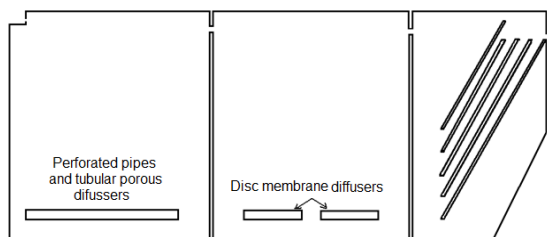


Fig. 1 Experimental Setup

The lamellar clarifier has a volume of 0,399 m³. The main purposes of the experimental research were: to verify the aeration systems' ability to homogenize the oxygen in the liquid environment of the bioreactor, a qualitative assessment of the intensity of the mixing process by determining the dissolved oxygen (DO) concentration evolution over time and comparing the three systems that provide oxygen for the experimental facility.

The DO concentration in the water mass was determined with Hach-Lange optical sensors, connected to a controller that allows the data (date, time, temperature, dissolved oxygen) display, storage and transfer.

Testing methodology: Comparison of different oxygen dispersion equipment from a technical and economic point of view can be performed using a uniform methodology to ensure reproducibility of test data [12]. The literature describes several methods for testing the oxygenation capacity (OC), some using stationary operating mode of aeration equipment as representative, others non-stationary regime.

In the steady state operation conditions of aeration systems in biological wastewater treatment (i.e. in the presence of microorganisms in activated sludge), oxygen consumption is measured by the difference between the oxygen concentration in the volume of air introduced into the tank and oxygen concentration in the gas leaving the bioreactor [15]. The method is difficult to apply due to difficulties in collecting the effluent gas.

The most commonly used methods for characterizing aeration systems are non-steady state, having as reference water parameters variation in time period while varying the aqueous environment. This method was used for the currently presented experimental research. As a liquid environment either bioactive environment (leachate and activated sludge) or a biologically inactive environment could be used.

The later method has the advantage of capturing the numerical values of the oxygenation capacity of various aeration systems, even knowing that these values do not necessarily have real significance bioactive conditions, but

with the certainty of their reproducibility [15]. As oxygen acceptor a reducing solution or pure water (sodium sulfite solution in the presence of cobalt or copper ions as catalyst) could be used. By using as acceptor the average sodium sulfite solution results presentation will be simplified due to the fact that the rate of oxygen absorption is virtually constant over time, the oxygen concentration in the water in the presence of the acceptor solution being constantly zero [15]. The disadvantage of this method is that the reaction between the oxygen and sodium sulfite may be lower under certain conditions (low temperature) than oxygen absorption even in the presence of larger quantities of catalyst. A further particular method used for fine-bubble oxygenation systems consists in dispersing nitrogen gas the water mass, which by reaction with the water oxygen leads to an increased oxygen deficit [14], [15].

The method used for determining the oxygenation capacity of aeration systems in clean water eliminates this disadvantage, but has the drawback that the oxygen transfer rate varies with increasing oxygen concentration, which may lead to misinterpretation of experimental data. The transient regime method was adopted and standardized as a testing technique and allows pertinent comparison of different oxygen dispersion equipment, while leading to reproducible results.

The method limitations are derived from theoretical assumptions underlying the test procedure; the method is applicable where mixing and oxygenation conditions are uniform throughout the water mass; if they are non-uniform the results are flawed to a degree of unevenness depending on the velocity and concentration distributions.

The overall mass-transfer coefficient K_{La} results by integration of the equation $dC / dt = K_{La} (C_s - C_0)$ as:

$$dC / dt = \frac{60}{t_2 - t_1} D_{t_1} / D_{t_2} \quad (1)$$

where D_{t_1} and D_{t_2} [mgO₂ / l] represent the oxygen deficit to saturation at time t_1 and t_2 . OC is given by:

$$O.C. = K_{La} C_{ss} V 10^{-3} \quad (2)$$

where $C_{ss} = 11,25 [mgO_2 / l]$ is the saturation concentration at a standard temperature of 10 °C, V - the water volume.

After carefully cleaning the bioreactor of all impurities, it was filled with tap water and the DO sensors were placed. The ability of the oxygenation equipment to homogenize the entire contents of the bioreactor is evaluated. For a qualitative assessment of the intensity of the mixing process the oxygen concentration variation over time is monitored; thus, it is necessary to increase the dissolved oxygen in the water from 10% to 80% of the saturation over a period of 10 to 30 min. The required amount of sodium sulfite for complete deoxygenation of the water volume was determined according to the stoichiometric relationship and increased by about 10-20% [15]. Then solution was added in the presence of cobalt chloride, as a deoxygenation reaction catalyst. The cobalt concentration did not exceed 0.05 mg / l, expressed as cobalt,

so that the error caused by interference with the Winkler test catalyst, standardized for determining the concentration of dissolved oxygen is below 5%.

During the operation phase the equipment monitored DO values directly by automated analyzers, each 30-60 seconds. At first, in the low concentrations domain samples are taken more frequently and near saturation concentration at longer time intervals.

The oxygen deficit values were determined by reporting the measured concentrations to the saturation value. The oxygen deficiency values with respect to time in semi-log coordinates are represented $\ln D_t = f(t)$. The curve slope is proportional to the mass transfer coefficient K_{La} [6], [7]

To reduce the possibility of errors, in particular by considering the values of the end of the line, only the variation deficit in the range 20-80% of the saturation concentration was considered.

Three values for the mass transfer coefficient for the three sampling points were determined. In order to determine the oxygenation capacity an average of these values was considered.

III. RESULTS AND DISCUSSIONS

A. Aeration Systems Testing

Testing the air dispersion systems was made by the method presented in the previous section. The excess sodium sulfite, a maximum of 10-20%, was consumed by introducing an amount of oxygen, taking as the starting point of the first oxygen concentration value, unrestrained of sodium sulfite.

Several sets of experimental determinations were carried out, for two different values of the airflow: $Q_{aer} = 1.2 \text{ m}^3/\text{h}$ and $Q_{aer} = 2.4 \text{ m}^3/\text{h}$. The airflow is maintained constant throughout all the measurements [15].

The dissolved oxygen measurement points were established considering the placement of the dispersion devices. The first sensor was placed in the central area of the tank, at a height of 0.4 m above the tank bottom and the second at 0.4 m of the above the tank bottom, near the back right corner of the bioreactor. The oxygenation capacity determined in the previously presented points covers, as values, the entire bioreactor volume.

The hydraulic regime strongly influences these determinations, which is why before starting deoxygenation, the system was operated for 3 hours, in order to reach permanent hydraulic regime.

In the first tank the perforated pipes were used as aeration systems. As can be seen in Fig. 2, in the first 25 minutes of aeration there is a rapid increase in the DO concentration in the water mass, this increase being much faster in the second than in the first tank. The justification for this increase is given primarily to the systems used for air dispersion (disc membrane diffusers), and secondly to the fact that the second tank influent has a higher DO concentration than in the first bioreactor.

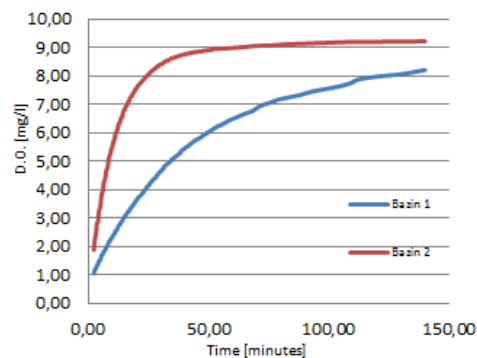


Fig. 2 The dissolved oxygen concentration variation over the time in the two tanks, for an air flow of $1.2 \text{ m}^3/\text{h}$, in the first measuring point (center, $H = 0.4 \text{ m}$). Perforated pipes were used in the first tank and disc membrane diffusers in the second one

In the next case, in the first tank the two tubular porous diffusers were used. The same measuring points and air flow as in the previous case were considered.

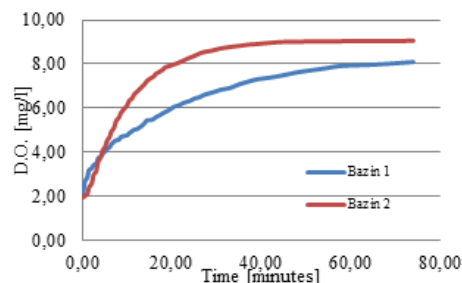


Fig. 3 The dissolved oxygen concentration variation over time in the two tanks, for an air flow of $1.2 \text{ m}^3/\text{h}$, in the first measuring point (center, $H = 0.4 \text{ m}$). Tubular porous diffusers were used in the first tank and disc membrane diffusers in the second one

In this case, for the first bioreactor, there is a more rapid increment of the D.O. value (during about 60 minutes), compared to the first case where the same air flow ($1.2 \text{ m}^3/\text{h}$) was considered, with a different dispersion system. This dispersion system is more efficient, but this flow of air in terms of quality for the intensity of mixing is not effective, because the dissolved oxygen has to increase from 10% to 80% of the saturation value over a period of 10-30 min [2], [5]. When it comes to the second tank, this criterion is met by the disc membrane diffusers, because 80% of the saturation concentration is acquired after about 23 minutes.

The same experimental steps were taken in the case of an air inflow of $2.4 \text{ m}^3/\text{h}$. The results can be seen in Fig. 4 (perforated pipes used in the first tank and disc membrane diffusers in the second one) and 5 (tubular porous diffusers were used in the first tank and disc membrane diffusers in the second one).

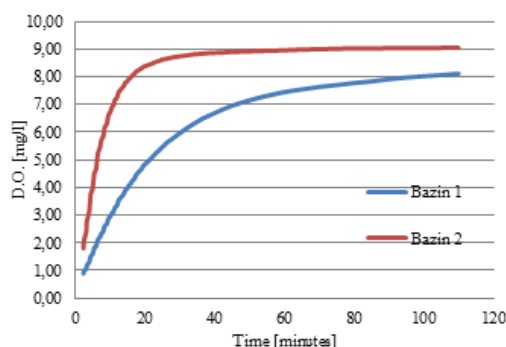


Fig. 4 The dissolved oxygen concentration variation over time in the two tanks, for an air flow of $2.4 \text{ m}^3/\text{h}$, in the first measuring point (center, $H = 0.4 \text{ m}$). Perforated pipes were used in the first tank and disc membrane diffusers in the second one

Compared to the first case, where airflow value is of $2.4 \text{ m}^3/\text{h}$, the necessary time to reach 80% of the saturation concentration at is lower for the first aeration tank, of about 95 minutes. When it comes to the second bioreactor, the time has a value of app. 17 minutes, and a reduction comparatively to the first case of 26%. Although the air inflow was doubled, the perforated pipes system still needs an extended timeframe to acquire 80% of the saturation concentration. That involves a high energy consumption, which has to be avoided considering the high costs.

As resulted for the $1.2 \text{ m}^3/\text{h}$ air inflow, when using the tubular porous diffusers with the increased air inflow to $1.2 \text{ m}^3/\text{h}$, the D.O. increases rapidly, but not with the same slope in the first tank as in the second one where the disc membrane diffusers are used.

When modifying the measurement point, to the right corner of each tank, the results were similar to the ones in the tank center. In this case also the best efficiency was met by the disc membrane diffusers used in the second bioreactor.

B. OC Evaluation

For an accurate assessment of the aeration system's performance it's necessary to determine the overall mass transfer coefficient, which can be considered equal to the slope of the curve for the concentration, ranging from 0.2 to 0.8 of the saturation value [15].

The oxygen to water transfer rate can be considered proportional to the driving force of the process:

$$dC / dt = K_{La} (C_s - C) \quad (3)$$

where C - the concentration of oxygen in the water at a certain time; C_s - the saturation concentration of oxygen in water; K_{La} - transfer rate constant (overall mass transfer coefficient). Rate of oxygen transferred by the aeration system is reported as it's OC, which is defined as the rate of oxygen transfer dC/dt , at an initial oxygen concentration (of 0) and standard conditions. It can be expressed either as the slope of the straight line represented by $v_0 = K_{La} \cdot (C_s - C)$ or $v_0 = K_{La} \cdot D$, where D is the oxygen deficit.

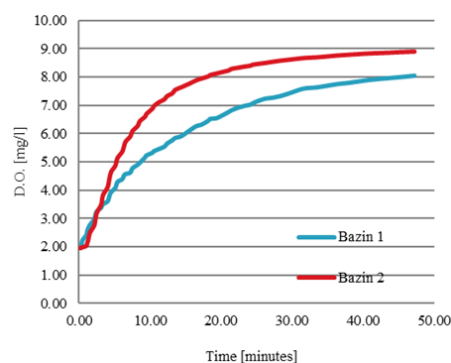


Fig. 5 The dissolved oxygen concentration variation over time in the two tanks, for an air flow of $2.4 \text{ m}^3/\text{h}$, in the first measuring point (center, $H = 0.4 \text{ m}$). Tubular porous diffusers were used in the first tank and disc membrane diffusers in the second one

If in (1) the partial derivatives are replaced with differentials by separation of variables, and integrated, a relation of the following form is achieved:

$$K_{La} = \frac{\ln D_1 - \ln D_2}{t_2 - t_1} \quad (4)$$

where D_1 is the oxygen deficit at t_1 and D_2 is the oxygen deficit at t_2 .

For all the experimental sets the overall mass transfer coefficient was determined. The results can be seen in Tables I-III.

Lower transfer coefficient values were obtained for the perforated pipes, justifying the low aeration performance of the tested equipment. In the case of the tubular porous air diffusers the values have increased comparatively to the previous situation, but they are significantly lower than the ones obtained for the disc membrane air diffusers.

TABLE I
THE RESULTS FOR THE PERFORATED PIPE DISPERSION SYSTEM

Q_{air} m^3/h	K_{La1} (h^{-1})	K_{La2} (h^{-1})	K_{Lamed} (h^{-1})	O. C. [kgO_2/h]
1,2	0,026274	0,02591	0,026092	0,14659
2,4	0,034657	0,039921	0,037289	0,20949

TABLE II
THE RESULTS FOR THE TUBULAR POROUS AIR DIFFUSERS

Q_{air} m^3/h	K_{La1} (h^{-1})	K_{La2} (h^{-1})	K_{Lamed} (h^{-1})	O. C. [kgO_2/h]
1,2	0,042724	0,030992	0,036858	0,20707
2,4	0,055875	0,053798	0,0548365	0,30808

TABLE III
THE RESULTS FOR THE TUBULAR POROUS AIR DIFFUSERS

Q_{air} m^3/h	K_{La1} (h^{-1})	K_{La2} (h^{-1})	K_{Lamed} (h^{-1})	O. C. [kgO_2/h]
1,2	0,09902	0,103369	0,1011945	0,56852
2,4	0,095801	0,121242	0,1085215	0,60968

For the dispersion system consisting of disc membrane diffusers the mass transfer coefficients obtained for both

experimented air flows have similar values. This indicates primarily a significant reduction in energy consumption for aeration because this system allows achieving similar performances with reduced air inflow. The highest mass transfer coefficient was found in the case of the disc membrane diffusers, of 0.1085215.

IV. CONCLUSION

The study aimed at evaluating the OC for different aeration systems. In the studied conditions, the highest aeration efficiency was the one of the disc membrane difussers, so using this system provides a much air flow requirement when compared to the other systems, hence the lower power consumption.

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