U.P.B. Sci. Bull., Series D Vol. 72, Iss. 3, 2010 ISSN 1454-2358

OXYGEN CONCENTRATION PROFILES IN COMBINED FINE AND MEDIUM BUBBLES AERATION SYSTEM

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Sistemele bifazice gaz-lichid sunt frecvent utilizate în epurarea apelor uzate şi tehnologiile de purificare, acolo unde este nevoie de concentraţii mari de oxigen în mediul lichid. Acest articol propune un model al transferului de oxigen din aer în apă pentru mediul bifazic lichid-bule de aer, pentru un sistem de aerare combinat, atât cu bule medii, cât şi cu bule fine, utilizat ca primă treaptă biologică într-o microstaţie de epurare, model de laborator. Modelul elaborat ţine cont de diametrul bulelor de aer şi de adâncimea de imersie a dispozitivului de insuflare a aerului comprimat, factori importanţi pentru procesul de transfer.

The biphasic gas-liquid systems are widely used in wastewater treatment and purification techniques where raised oxygen concentrations into the aqueous environment are required. This paper proposes a model for oxygen transfer from air into water in the biphasic environment liquid-air bubbles level, for a combined aeration system with fine and medium size bubbles, used as a first biological stage by a wastewater treatment micro plant, laboratory model. The elaborated model takes into account the air bubbles diameter and the immersion depth of the equipment for the injection of the compressed air, essential factors for the transfer process.

Keywords: biological reactor, oxygen concentration profiles

1. Introduction

In biochemical processes, the oxygen injected by the aeration equipment is consumed by the mineralizing bacteria and for an energy-efficient process, it is necessary to maintain the concentration of residual dissolved oxygen constant within the range of 1 - 3 mg O_2 /l [1]. For a proper operation the aeration equipment must be optimally adjusted to the geometrical parameters of the aeration tank and to the treatment technology applied.

Aeration is an essential process in the majority of wastewater treatment plants and accounts for the largest fraction of plant energy costs, ranging from

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45% to 75% of the plant energy expenditure, [2 and 3]. Aeration systems transfer oxygen into a liquid media by either diffusing gas through a gas–liquid interface, or dissolving gas into the liquid solution using a semi-permeable membrane. Environmental technologies usually 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. Surface aerators shear the wastewater surface producing a spray of fine droplets that land on the wastewater surface within few seconds and over a radius of a few meters. Diffusers are nozzles or porous surfaces placed on the tank bottom that release bubbles traveling towards the tank surface. In general, bubbles are considered fine when their diameters are less than 5 mm. Fine-pore diffusers have become the most common aeration technology in wastewater treatment in developed countries. They have higher efficiencies per unit energy consumed and are usually installed in full floor configurations, which enhance their operating efficiency. Fine-pore diffusers have two important disadvantages: the need for periodic cleaning and the large negative impact on transfer efficiency from wastewater contaminants. The implications of fine-pore diffuser ageing and the benefits of cleaning have been previously discussed [4].

A required condition for an optimal economic operation of the biological reactor is the correlation between the transferred oxygen with the one consumed during the metabolic process of organic matter degradation. The mathematical modeling of the physical, chemical and biological processes that occur in the aeration tanks of the wastewater treatment plants is very difficult due to their complexity. Into the aerobic biological reactors the oxygen consumption varies in time and space as a result of the non-uniformity of the influent biodegradable organic matter or due to the changes of the kinetic relations between the biomass growth and the substrate removal rates. For real and normal operation conditions a dynamic equilibrium is established between the oxygen transferred and its consumption through mineralization reactions, reaching in time a stationary operation regime.

Activated sludge process is the most widespread technique for biological wastewater treatment. In large wastewater treatment plants, the aerobic degradation is often performed in channels or closed-loop reactors [5]. Different types of activated sludge reactors have been presented in the literature [6]. The channel reactor with bottom aerators is one of the oldest types of systems and is particularly well adapted to large plants. Due to the shape and the size of these units, there is an effect of hydrodynamics on the efficiency of the pollution removal, as concentration gradients are experimentally observed, for nutrients as well as for oxygen [7]. The effect of the flow behavior on the efficiency of wastewater treatment has often been pointed out [8]. Makinia and Wells [9] also showed the impact of the flow conditions and variations in the aeration intensity on changes in the predicted dissolved oxygen (DO) concentrations in a full-scale activated sludge reactor. Many studies have been made in order to describe the hydrodynamics of these reactors. Because of its design, the flow behavior of the channel reactor is well represented by the plug flow with axial dispersion model, the equivalent perfect mixing cells in series model or alternatively by the perfect mixing cells—in series with the back-mixing model.

The main purpose of the aeration equipment tests in standard operation conditions is to estimate the oxygen concentration variation in time and space. In literature [1] are described various testing methods for determining the oxygenation efficiency. Some of these methods use as representative the stationary operation mode for the aeration equipment while others give the non-stationary one as reference. The test method considered for this paper is based on the removal of the dissolved oxygen from the tap water volume in the aeration tank by addition of chemicals (sodium sulphite in the presence of cobalt ions) followed by reaeration to near the saturation level. The dissolved oxygen inventory of the water volume has to be monitored during the reaeration period by measuring the dissolved oxygen concentrations at several determination points selected to best represent the tank contents. For this scenario a mathematical model for non-stationary regime was elaborated. At this moment in literature are given many experimental results for the aeration tests. As it regards the mathematical models most of researches focus on determining the concentration profiles in the aeration tank during operation [9] or the oxygen transfer from a single bubble. The model proposed in this work takes into account combined medium and fine bubbles aeration system used in the first biological stage of a dual biological wastewater treatment model installation. It can be used to predict the oxygen concentration profiles for the studied reactor during the reaeration period that follows the complete deoxygenating of the water body.

2. Mathematical model

A model for the theoretical predicting of the oxygen concentration profiles in the medium bubbles aeration tank using the dispersion equation is developed. A parallelepiped–shaped aeration tank with longitudinal flow and with aeration from the bottom is considered (fig. 1), similar with that used in a laboratory model. The air is dispersed in the water using combined pneumatic equipment consisting of two pipes with perforations and two tube pore diffusers, connected to a blower.

The following hypotheses are taken into account: hydraulically permanent motion; unidirectional horizontal motion; no stationary system as to mass transfer; perfect mixing in aeration tank.

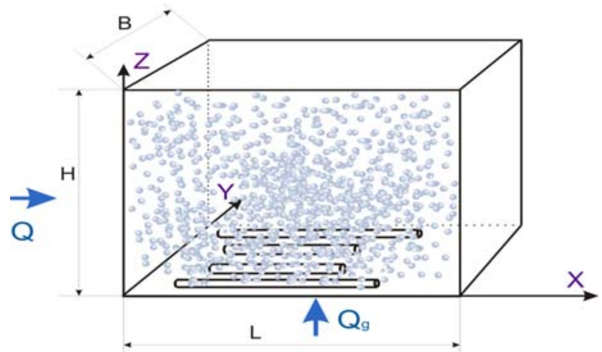

Fig. 1. Aeration tank.
Q- water flowrate; B- width of the tank; H – depth of the tank; L – length of the tank;
Q_g – air flow rate.

The general oxygen dispersion equation is:

$$\frac{\partial \overline{C}}{\partial t}+\frac{\partial}{\partial x}\left(\overline{u}\overline{C}\right)+\frac{\partial}{\partial y}\left(\overline{v}\overline{C}\right)+\frac{\partial}{\partial z}\left(\overline{w}\overline{C}\right)=\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial \overline{C}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial \overline{C}}{\partial y}\right)+\frac{\partial}{\partial z}\left(\varepsilon_z\frac{\partial \overline{C}}{\partial z}\right)+$$
$$+D_m\left(\frac{\partial^2\overline{C}}{\partial x^2}+\frac{\partial^2\overline{C}}{\partial y^2}+\frac{\partial^2\overline{C}}{\partial z^2}\right)+S(x,y,z,t), \qquad (1)$$

where C – the oxygen concentration, ε_x – the axial dispersion coefficient, ε_y - the transversal dispersion coefficient, ε_z – the vertical dispersion coefficient, S – the consumption of oxygen, Dm – the mass diffusion coefficient. The upper bar means that the respective quantities are averaged due to the turbulence.

The following additional modeling hypothesis can be formulated in order to resolve the Eq.1:

- planar movement process (water flows on the Ox-axis with the constant velocity u);
- the terms for the transversal turbulent dispersion are neglected because their very small values against similar phenomena on Ox and Oy;
- due to upward movement of air bubbles occurs a gas lift phenomenon that enhances mixing and oxygen transfer into water;
- in the Eq.1, the component *v* of velocity is replaced with the raising velocity of air bubbles, *w;*
- the axial dispersion occurs due to the multiphase flow along Ox axis and upward movement of gas bubbles;
- there is perfect mixing of phases.

The dispersion equation in these conditions becomes:

$$\frac{\partial \bar{C}}{\partial t}+\frac{\partial}{\partial x}\left(\bar{u}\bar{C}\right)+\frac{\partial}{\partial y}\left(\bar{w}\bar{C}\right)=\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial \bar{C}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial \bar{C}}{\partial y}\right)+D_m\left(\frac{\partial^2 \bar{C}}{\partial x^2}+\frac{\partial^2 \bar{C}}{\partial y^2}\right)+S(x,y,t), \tag{2}$$

Since the air is introduced at the bottom of the tank as fine bubbles that generate through their movement hydrodynamic currents that will return to the bottom of the basin assuring the spreading and homogenization of the oxygen into the entire liquid phase, it can be estimated that $\varepsilon_x=\varepsilon_y$. For the numerically integration of the Eq. (2) a customized program is written using FlexPDE software, [13]. FlexPDE is a "scripted finite element model builder and numerical solver". It means that from a script written by the user, FlexPDE performs the operations necessary to turn a description of a partial differential equations system into a finite element model, solve the system, and present graphical and tabular output of the results. FlexPDE has no pre-defined problem domain or equation list. The choice of partial differential equations is totally up to the user, [15].

The constants in the equation (2) are determined from the design parameters of the aeration tank using the correlations available in literature. The horizontal flow velocity of the liquid is simply determined, as the water flow rate and the flow section are known from the dimensioning relations. The biological reactor was designed to operate for a water flow rate of 0,1 m^3/h and for a maximum flow rate of injected air equal to 4,5 m^3/h. The resulted geometrical parameters of the reactor are L=0,74 m, H=0,85 m and B=0,97 m. As it regards the vertical velocity of the water, accordingly to Linek V. et. al. [10], it can be estimated as 0,65 of the bubble rise velocity. This combined aeration equipment can provide air bubbles with a mean diameter of 2,3 mm [11,12], that will raise to the free surface with a velocity equal to 0,272 m/s. This value was estimated based on the relation proposed by J. Dudley [7] and later by Chanson [13]:

$$w_b=\sqrt{\frac{2\cdot\sigma}{\rho\cdot d_b}+0,5\cdot g\cdot d_b} \tag{3}$$

With the superficial air-water tension $\sigma=0,0726\,N/m$ and a liquid density of $\rho=1000\,kg/m^3$. The above mentioned relationship is valid for bubbles with a diameter larger than 1 mm; the velocity was determined for the value of the mean diameter obtained by using the combined aeration system. For the axial dispersion coefficient various correlations are available, but a complex one is given by Lemoullec at. al., [14]:

$$\frac{\varepsilon_x}{(H+B)}=0.0115a\Phi^m\left(1+\frac{h_d}{L}\right)^{-3}\left(\frac{Q_g}{LB}\right)^{-0,34} \tag{4}$$

Where h_d is the immersion depth of the diffusers. The constants *a* and *m* (Table 1) are correlated with Φ, given by the following relation:

$$\Phi = h_d\left(\frac{Q_g}{BH}\right)\left(\frac{h_d}{H}\right)^{0,5}\left(\frac{H}{B}\right)^{0,33} \tag{5}$$

and with diffuser type.

Table 1

The values of the coefficients a and m depending of the diffuser type and the calculated value of Φ

Diffuser type	Φ (cm^2/s)	m	a
Fine bubble diffusers	<20	0,64	7,0
	>20	0,46	12,0
Coarse bubble diffusers	<20	0,78	3,5
	>20	0,56	4,9

The aeration equipment is a source of oxygen; its influence is considered within the script through the Neumann boundary conditions imposed at the air injection surface. This condition may be considered because the value of the transferred flux is not time dependent in this case given that the experimental tests will be performed at constant pressure and air flow rate. After these considerations the equation (2) can be rewritten as:

$$\frac{\partial\bar{C}}{\partial t}+\frac{\partial}{\partial x}\left(\bar{u}\bar{C}\right)+\frac{\partial}{\partial y}\left(\bar{w}\bar{C}\right)=\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial\bar{C}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial\bar{C}}{\partial y}\right)+D_m\left(\frac{\partial^2\bar{C}}{\partial x^2}+\frac{\partial^2\bar{C}}{\partial y^2}\right) \tag{6}$$

3. Numerical results

Various oxygen flux conditions were analyzed, for the above mentioned configuration of the reactor but also for reactors with higher length: 1,5 m respectively 3 m, maintaining the same configuration of the aeration system

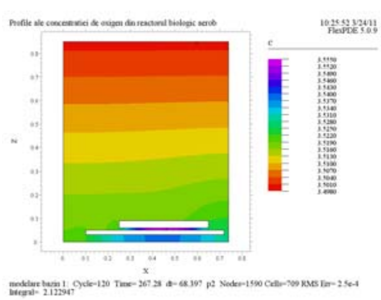

Fig. 1. Model results for the first 5 minutes.

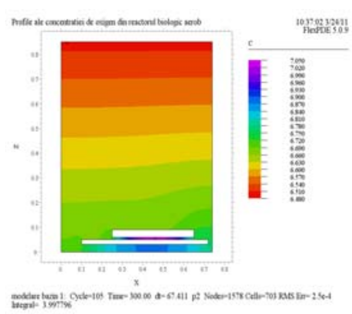

Fig. 2. Model results for 20 minutes of reaeration.

The results plotted in figure 1 and 2 were obtained for a value of the transferred oxygen flux of 0,001 mg O_2/m^4. The maximum oxygen concentration is obtained for the bottom area, case that could correspond to the experimental reality. As the bubbles ascend to the free surface they transfer important oxygen amounts and draws up large liquid quantities that will return to the lower part of the reactor with an increased oxygen concentration. After 20 minutes of reaeration (fig.2) oxygen concentration approaches the saturation value.

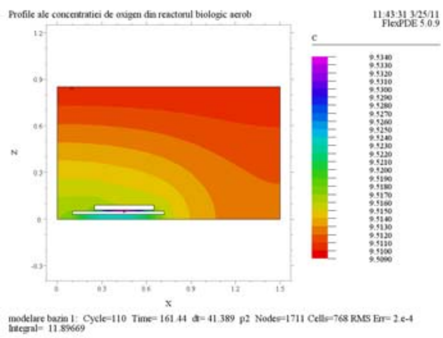

Fig.3. Concentration profiles for a higher flux and a different geometry.

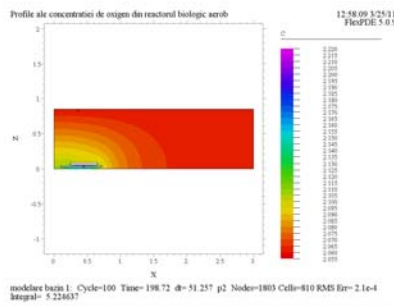

Fig.4. Concentration profiles for a reactor with a length of 3 m.

Figures 3 and 4 present the case of aeration tank with the length of 1,5 m respectively 3 m, equipped with the same aeration system. The results for the smaller tank (1,5 m) shown that the dimensions and geometry are appropriate for the process, the oxygen is homogenously distributed into the entire water body whilst the case of the 3 m reactor is the case of an inadequate operation. For this last scenario it is obvious that the aeration equipment is under - dimensioned and its influence in the major part of the reactor is insignificant.

4. Conclusions

The proposed model includes important factors for the mass transfer process such as bubble diameter and the immersion depth of the diffuser. The results can be used in the optimization and control of the biological wastewater treatment operation, for appropriate positioning of dissolved oxygen sensors, and in the design stage for choosing the appropriate aeration equipment and its location in the tank. The future works will be focused on validating this model with the experimental data obtained on the model installation.

R E F E R E N C E S

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