Modelling and Simulation of Organic Matter Biodegradation Processes in Aeration Tanks with Activated Sludge

MIHAELA ILIE1*, DAN NICULAE ROBESCU2, GINA GHITA1
1 National Institute of Research-Development for Environmental Protection – ICIM, 294 Splaiul Independentei, 060031, Bucharest, Romania
2 University Politehnica of Bucharest, Power Engineering Faculty - Hydraulics, Hydraulic Machinery and Environmental Engineering Department, 313 Splaiul Independentei, 060042, Bucharest, Romania

Biological treatment process modelling is a complex process in which biochemical and hydrodynamic factors are in a strong interdependence. Mathematical models that are known at present and describe the activated sludge treatment processes do not consider the influence of hydrodynamic factors. This paper presents modelling and simulation of organic matter biodegradation processes, from wastewater in the aeration tanks within the treatment plants, also considering the influence of hydrodynamic parameters.

Keywords: mathematical simulation, dissolved oxygen, active sludge, wastewater treatment, biodegradable organic substrate

In the activated sludge treatment processes, the air supply system is the main factor for energy costs, representing 60% of total energy consumption from the activated sludge systems [1]. Dissolved oxygen concentration is one of the most important control parameters of the activated sludge treatment system. Treatment efficiency depends on the efficiency of organic matter degradation in the aeration tank and on the efficiency of biomass separation from the treated water in the secondary clarifier [2].

In wastewater treatment processes, the activated sludge aeration provides oxygen, as final electron acceptor, for bacterial metabolism and consequently controls organic matter degradation [3]. Theoretically, the amount of oxygen that has to be transferred to the aeration tank has to be equal to oxygen amount necessary for microorganisms from the activated sludge system to oxidize the organic matters. In practice, oxygen transfer to the liquid mass is low and only a small oxygen amount from the demand will be used by microorganisms [4].

The first kinetic study concerning the limitation of bacterial growth by substrate concentration, started with Monod research carried out on a single cultivated bacterial culture, in static conditions, in the reactor, in which there is introduced a substrate containing one organic matter [5]. These research studies have led to drawing up bacterial growth models that, with some changes, represent the basis of relations used in modelling the process of wastewater treatment with activated sludge.

It is to be mentioned that the only way for providing a right basis for design and running is to identify a real description of process mechanisms under microbial kinetics and material balance conditions [6].

Technical literature mentions at present, a large number of mathematical models which describe the biological treatment processes, the most recent of them being activated sludge biological models ASM1, ASM2 and ASM3 [7].

Major differences between these models consist in: kinetic expressions used in order to specify the organic matter consumption and activated sludge growth, selecting plant elements in order to perform the mass balance and in the way in which the flow within the aeration tank is carried out. The influence of hydrodynamic factors is neglected although the medium in which biochemical reactions take place is an aqueous one. Hydrodynamic factors may lead to intensifying the transfer process both of oxygen and organic matter to floc and cells, mixing and homogenization of phases and to a better contact between floc and organic matter [8].

Mathematical simulation of oxygen demand in treatment processes

Modelling of physical, chemical and biological processes that occur in aeration tanks from wastewater treatment plants may be carried out by considering the main physical, chemical or biochemical phenomena, specifying the reaction of interaction with other phenomena.

Microorganisms within the activated sludge floc performs all the biochemical reactions only if oxygen and biodegradable organic substrate may reach the floc centre where oxygen concentration must not be less than critical value of 0.5 mg/L [9].

Oxygen demand varies with time and space in an aeration tank with activated sludge. Time variations may be assessed by means of statistic analyses of collected data concerning the influent load from the point of view of biodegradable organic matters indirectly expressed by Biochemical oxygen demand (BOD). Space variations depend on kinetic relations between biomass growth rates and substrate removal rates, flow conditions and hydraulic retention time [10].

If one considers oxygen diffusion and dispersion from the air introduced in water mass, as the main phenomenon, equation will be as follows [8]:

\[ \frac{\partial C}{\partial t} + \nabla \cdot (\hat{\nu} C) + \frac{\partial}{\partial x} \left( \hat{\nu} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( \hat{\nu} \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left( \hat{\nu} \frac{\partial C}{\partial z} \right) = D_m \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \right) + R(x, y, z, t) \] (1)

where:
- \( x, y, z \) - coordinates of the considered point from the aeration tank;
- \( C(x,y,z,t) \) - the concentration of oxygen from the aqueous medium;
- \( D_m \) - diffusion coefficient in the medium;
D - oxygen diffusion constant from air to water, its values depending on temperature ($D_m = 0.203 \text{ m}^2/\text{s} \text{ at } 20\degree \text{C}$; $D_m = 0.155 \text{ m}^2/\text{s} \text{ at } 10\degree \text{C}$ and $D_m = 0.18 \text{ m}^2/\text{s} \text{ at } 15\degree \text{C}$); $\varepsilon_x$, $\varepsilon_y$, $\varepsilon_z$ - coefficients of longitudinal, transverse and vertical dispersion on the fluid flow; $u$, $v$, $w$ - components of the speed vector; $R(x,y,t)$ - oxygen source or demand in biochemical reactions.

Size averaging is carried out in accordance with time because the flow condition is a turbulent one with size variations in time $u = u + u'$ for speed, $c = c + c'$ for concentration, etc; $u = \frac{1}{T} \int_0^T u dt$.

Values of dispersion coefficients depend on turbulent state of aqueous medium movement, these values being higher than the molecular diffusion constant. A complete solution of this equation, at which continuity and movement equations have to be attached is impossible to be obtained due to dispersion coefficients dependence on flow conditions, nature, shape and size of the dispersed particles, as well as on physical characteristics of media. This is why simplified models are most frequently used.

For a parallelepipedic aeration tank, having air dispersion devices at the air tank basis, the movement is identically made in all the plans which are parallel to a basic vertical plane. Wastewater enters with speed “u” - on the direction of Ox axis, maintaining it constant along this axis. It will be considered that the rate of liquid mass entrainment, by the effect of gas-lift of the air bubble jet, “v” - on the vertical direction is constant and has the same value as the rate of a gas bubble lift.

This model considers the case of an ideal biological reactor, correctly dimensioned in shape and size, regarding the process needs. It also assumes to be equipped with a pneumatic oxygenation plant having a density of 2.5-3 fine bubble dispersing devices/m$^2$ of reactor plan area. Experience has proved that there are no “dead water” and stagnant areas in which biomass breaking down phenomena produce. A short-circuit current – by-pass areas – can not be present due to the movement on vertical and horizontal axis.

The movement of the aquatic environment within the aerobic biological reactor is a very complex one. Over the transport move having the speed $u$, which may be considered like piston type, a movement on the tank vertical line is overlaid on both directions of it. Air is injected as bubbles in the aqueous environment and rises upward on the vertical line. It carries along, by a gas-lift effect, large amounts of water, towards layers that have a lower hydrostatic pressure. On lateral sides of air dispersion devices, the aqueous environment moves downward on the vertical axis; after that, it is carried along again towards free areas of gas bubbles. For gas bubbles with a 0.2 mm diameter, the lifting speed is 0.35 m/s; this determines the liquid to be carried along with a speed of 0.2 m/s.

The elaborated model takes into account the complete admixture hypothesis, justified by transport movement on the horizontal line, combined with vertical movements of phases belonging to the polyphased environment, carried along by gas bubbles. This helps to avoid building up stagnation and “dead water” areas and supports the contact between sludge flocks, oxygen and organic matter.

In the bi-dimensional dispersion equation (1) becomes:

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x}(uC) + \frac{\partial}{\partial y}(vC) = \frac{\partial}{\partial x}\left(\varepsilon_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_y \frac{\partial C}{\partial y}\right) + \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + R(x,y,t)$$

The term $R(x,y,t)$ is that which includes the influence of chemical oxidation reactions, as well as of the biochemical ones of organic matter degradation in the presence of oxygen provided by forced convection by an aeration equipment. It might be adopted with different mathematical forms, but the most convenient one, set by different numerical integrations is $R(x,y,t) = - kC$. The factor “k” might have many values, this leading to setting up the optimal value in order to obtain some correct distributions of oxygen in the water mass from the aeration tank.

Together with the concentration of oxygen dissolved in wastewater from the aeration tank, the turbulence contributes to the increase of activated sludge metabolic activity. Besides maintaining the activated sludge suspension in the medium, turbulence has an important role, namely to contribute, by mixing, to the contact between food, oxygen and microorganisms.

If the biological reactor and specific oxygenation plant are correctly dimensioned, stagnation areas will not be present within this tank.

In the dispersion equation, there may be expressed the factor that multiplies the partial derivative of the second order, as $(D_m + D_{in}) = Nux [111]$, where Nu is the dimensionless number of Nusselt, $Nux = \frac{D_m + D_{in}}{D_{in}}$. This similitude number mentions how many times the turbulent diffusion ($D_{in}$) is more intense than the molecular one ($D_m$). The expression of Nusselt numbers are introduced for axis Ox and Oy respectively.

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x}(uC) + \frac{\partial}{\partial y}(vC) = \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + R(x,y,t)$$

This model takes into account the hydraulic conditions, by $u$, $v$ velocities and by values of Nusselt number which considers the intensity of eddying flow.

Equation (2) of oxygen dispersion in the water mass may be written as (3), in which expression of Nusselt numbers are introduced for axis Ox and Oy respectively.

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x}(uC) + \frac{\partial}{\partial y}(vC) = \frac{D_m}{Nux} \frac{\partial^2 C}{\partial x^2} + \frac{D_m}{Nuy} \frac{\partial^2 C}{\partial y^2} + R(x,y,t)$$

This model takes into account the hydraulic conditions, by $u$, $v$ velocities and by values of Nusselt number which considers the intensity of eddying flow.

Equation (3) of oxygen dispersion in the wastewater treatment plant is modified by considering the process of oxygen demand from the water mass, by mineralizing bacteria. The term which represents oxygen demand due to biochemical processes is considered to be under the form of Monod relation (4) for the case of wastewater organic matter degradation without inhibitors [7,12-14].

$$R(x,y,t) = -\mu_m \frac{Y - S}{Y + S + Ks} X$$

where:

$\mu_m$ – maximum specific rate of heterotrophic microorganism growth, [T$^{-1}$];
$X$ – active heterotrophic biomass, [ML$^{-3}$];
$Ks$ – saturation constant, numerically equal to substrate concentration when reaches the first half of maximum growth rate, [ML$^{-3}$];
$S$ – biodegradable substrate concentration, [ML$^{-3}$];
$Y_m$ – factor of substrate conversion in biomass (formed biomass/consumed substrate), [M(CCO)X/M(CCO)S].
Having these in view, the dispersion equation becomes:

\[
\frac{\partial C}{\partial t} + \frac{\partial}{\partial x}(uC) + \frac{\partial}{\partial y}(vC) = D_m N_{ux} \frac{\partial^2 C}{\partial x^2} + D_m N_{uy} \frac{\partial^2 C}{\partial y^2} - \mu_m \frac{1 - \frac{S}{K_s}}{Y} \frac{C}{C_s} + \frac{1 - \frac{S}{K_s}}{Y} \frac{C}{C_s}
\]

(5)

This model is not stationary from chemical point of view, but is permanent from the hydrodynamic point of view. Modelling is carried out in time (the time period appears within the integration program) and space – the variation of concentration \( C \) is observed on the whole surface of the tank vertical line. Concentration variation in the biomass is reduced, this aspect leads to neglecting it (it grows as a result of bacterial multiplication).

Equation (5) will be numerically integrated by using the FlexPDE program. The results of these numerical integrations are shown below, for an aeration tank having standard dimensions, 20 m length and 4 m height, which is met frequently in wastewater treatment plants. Values of organic load, in process modelling and simulation have been considered to range between 100 ÷ 10000 mgCBO/l, these could have been determined by trials, by a method suggested by Ekama [7]. Values of the activated sludge concentration have also been different. For kinetic parameters \( \mu_m, K_s \) and \( Y \) there were considered specific values used in the activated sludge model ASM1 [15]. The answer of the biological treatment stage, to different loads of wastewater is followed in this way.

Considering the hydrodynamic parameters and introducing the term of oxygen demand as a result of microbial activity, in the dispersion equation represents a novelty in the field of modelling and simulation of organic matter degradation process. This complex process modeling considers the following: physical phenomenon of mass molecular and turbulent transfer, dispersion of oxygen diffused in the aqueous medium, as well as aspects of oxygen demand within the cellular metabolism for biodegradable organic matter degradation.

**Simulating oxygen demand for organic matter degradation**

**Case A:** Integrating equation (5), for the following parameters:

- \( u = 0.2 \)
- \( v = 0.8 \)
- \( N_{ux} = 10 \)
- \( N_{uy} = 1200 \)
- \( D_m = 0.203 \)
- \( S = 8000 \)
- \( X = 3000 \)
- \( \mu_m = 6 \)
- \( K_s = 20 \)
- \( Y = 0.67 \)
- \( C_s = 10 \)

**Case B:** Integrating equation (5), for the following parameters:

- \( u = 0.2 \)
- \( v = 0.6 \)
- \( N_{ux} = 10 \)
- \( N_{uy} = 100 \)
- \( D_m = 0.203 \)
- \( S = 200 \)
- \( X = 400 \)
- \( \mu_m = 1.2 \)
- \( C_s = 10 \)

Fig. 1. Distribution of concentration and demand of oxygen from the aeration tank with activated sludge, to the biological process of organic matter degradation. Oxygen demand is high due to a high organic load – this leads to maintaining the residual concentration in the aqueous medium, almost zero. This is a case of improper aeration tank operation and the sludge stifles itself.

Fig. 2. There are observed high values of residual oxygen concentration, being almost to saturation and this indicates that the aeration tank volume is too large comparable to process needs or this is an accidental case, when wastewater has a very low concentration of organic matters.
Conclusions

Modelling and simulation of biological processes of biodegradable organic matter degradation is possible and this paper presents the results obtained by numerical integration of process specific equations. They may be used in practice for automatic control and development of processes which directly base on the correlation of physical, chemical and biochemical factors.

The elaborated model takes into account the complete admixture hypothesis, justified by transport movement on the horizontal line, combined with vertical movements of phases belonging to the polyphased environment, carried along by gas bubbles. This helps to avoid building up stagnation and “dead water” areas, and supports the contact between sludge flocks, oxygen and organic matter.

Introducing the term of oxygen demand as a result of microbial activity, in the dispersion equation represents a novelty in the field of modelling and simulation of organic matter degradation process. This complex process modelling considers the following: physical phenomenon of mass molecular and turbulent transfer, dispersion of gas diffused in the aqueous medium, as well aspects concerning oxygen demand existing in the aqueous medium within the cellular metabolism. This model becomes closer to the reality of the process carried out in the air tank of the treatment stage; it might be used in practice for automatic control and development of processes which directly base on the correlation of physical, chemical and biochemical factors.

The model allows determining the values of residual oxygen concentration in the aqueous environment on vertical and horizontal axes of the tank for different conditions of the biochemical demand. One can specify the optimal tank status and the depth of oxygen well concentration on the aeration tank length is low. One mentions that on the basic area, an oxygen concentration of 0.5 mgO₂/L occurs, which allows bacteria to live in the activated sludge. A correlation between geometric parameters and physical and bio-chemical ones is present in this case.

References

1. RIEGER, L., ALEX, J., GUJER, W., SIEGRIST, H. Modelling of aeration processes belonging to the polyphased environment, carried the horizontal line, combined with vertical movements of admixture hypothesis, justified by transport movement on physical, chemical and biochemical factors. This complex process is novel in the field of modelling and simulation of organic matter degradation process. 2. DIGNAC, M.F., GINESTET, P., RYBACKI, D., BRACKET, A., URBAIN, V., SCRIBE, P. Fate of wastewater organic pollution during activated sludge treatment: nature of residual organic matter. Water Research, 34, nr. 17, 2000, p. 4185
11. ROBESCU, D.N., LANLI, S., ROBESCU, D., CONSTANTINESCU, I. Tehnologi, instalații și echipamente pentru epurarea apei, Editura Tehnică, București, 2000, p. 204

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