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Proffesional paper
UDC :628.353.1/.3.09.001.57

Modelling of biological reactor for municipal wastewater treatment

Water resources management is an ongoing, complex issue, which is of essential importance to secure successful and sustainable development in the environmental engineering. The knowledge of the modern treatment procedures and eco-separation processes is a crucial factor for defining the appropriate wastewater treatment operations.

This work presents a set up of a mathematical model of the process of rural wastewater biological treatment. The first design stadium reflects the mathematical modeling of a CMAS bioreactor as aeration tank with sludge recirculation. The second stadium represents practical implementation of the mathematical model - dimensioning real rural wastewater treatment system with capacity of 5.000 P.E. The main design accent was placed on the dimensioning of the CMAS bioreactor in order to achieve high-efficient removal of dissolved organic components.

***Key words**: CMAS bioreactor, mathematical modeling, process design*

1. INTRODUCTION

In latter day, modern society, wastewater treatment and water resource management are being discussed and analyzed. Knowing the origin and composition of wastewaters is essential precondition to determine the processes and operations included in the wastewater treatment plants. The goal of this work is to deepen the knowledge of application of adequate, precise process eco-technologies in the wastewater treatment from scientific and applicative aspect. This represents an ongoing problem in the modern process eco-engineering.

The identification of adequate wastewater management for small communities is a complex problem as it demands integration of data from different sources, such as community needs, receiving environment, landscape, or available and affordable wastewater treatment technologies. By application of primary treatment (mechanical, physical, chemical methods), dissolved or colloid dispersed organic matter cannot be eliminated from the rural wastewater. Therefore, a secondary treatment processes are introduced, which are basically biochemical processes. There are two common types of aerobic systems of wastewater secondary treatment known as fixed film (fixed bio-film) systems and suspended growth (suspended biomass growth) systems [1].

A flow scheme of a suspended biomass growth system is presented in Figure 1.

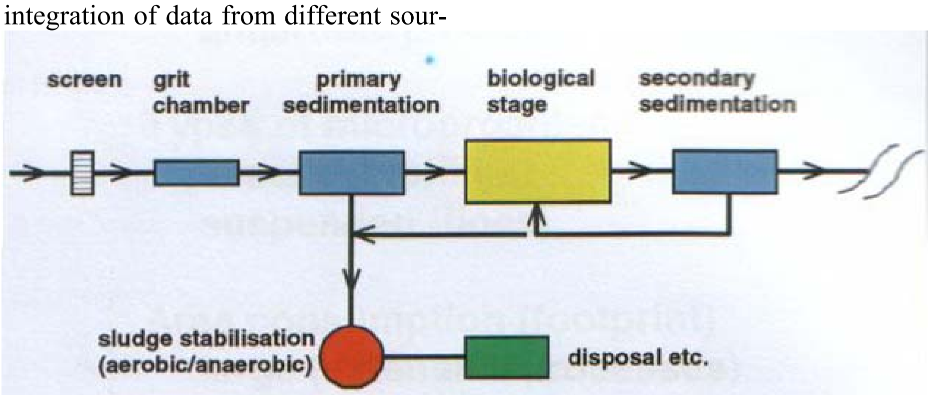

Figure 1 - Flow scheme of a suspended growth system

Defining the most appropriate wastewater treatment system is a complex task in the environmental engineering, as it incorporates various factors such as: availability of necessary construction area, terrain configuration, existence of appropriate sewage system, energy consumption and efficiency of the wastewater treatment plant, biochemical characteristics of the wastewater etc.

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Paper received: 15.06.2011

An activated sludge system is one of the most common suspended growth wastewater treatment systems applied in cities, towns and smaller municipalities. It consists of all the treatment stages presented in Figure 1 and represents a system that has many advantages as it provides high removal efficiency of both - solid particles and dissolved organic and inorganic matter. Furthermore, in aspect of energy consumption, this treatment system has certain flexibility regarding the biological stage of the treatment through application of adequate process optimization and installment of automatic process control.

Considering the advantages of the discussed wastewater treatment system, which has a biological treatment stage conducted in a completely mixed biological reactor, the goal of this work is to produce an adequate model of the bioreactor. This model will be used for dynamic simulation in order to obtain results for different operating regimes.

2. EXPERIMENTAL PART

The studied case of a wastewater treatment plant, located in the western region of R. of Macedonia, includes a secondary (biological) treatment of the communal wastewater, conducted in a typical "suspended growth" system - Activated Sludge system, based on the CMAS (Completely Mixed Activated Sludge) model, as shown in Figure 2.

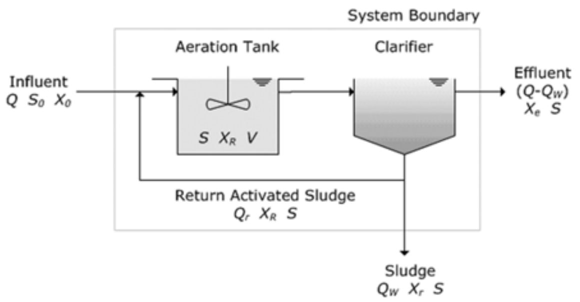

Figure 2 - System boundary of the biological treatment stadium

3. RESULTS AND DISCUSSION

Modeling of the CMAS bioreactor

Setting up a mathematical model of the CMAS (Completely Mixed Activated Sludge) bioreactor (aeration tank) introduces the first phase of the process design [2, 3]. The studied bioreactor represents continuous flow system with recirculation. Resulting design equations of the CMAS bioreactor are derived from the component mass balances of the systems biomass and substrate [1].

Mass balance of biomass:

$$Q \cdot X_0 + V \cdot \frac{dX}{dt} = (Q - Q_w) \cdot X_e + Q_w \cdot X_w$$

Mass balance of substrate:

$$Q \cdot S_0 + V \cdot \frac{dS}{dt} = (Q - Q_w) \cdot S_e + Q_w \cdot S_w$$

In order to introduce justified simplifications to the mass balance expressions the following technically legitimate assumptions are taken into consideration [4]:

- Biomass concentration in the influent and effluent is negligible, X_0, $X_e = 0$;
- Considering the type of the bioreactor (CSTR) substrate concentration in the aeration tank volume is uniform and equals the substrate's outlet concentration value $S = S_w = S_e$;
- All biochemical reactions are conducted in the aeration tank;

According the implementation of the presented assumptions to the mass balance expressions of the biomass and substrate, the following equations are obtained:

$$S = \frac{K_s \cdot (1 + k_d \cdot \theta_c)}{\theta_c \cdot (\mu_m - k_d) - 1}$$

$$\theta_c = \frac{K_s + S}{S \cdot (\mu_m - k_d) - K_s \cdot k_d}$$

$$X = \frac{\theta_c \cdot Y \cdot (S_0 - S)}{\theta \cdot (1 + k_d \cdot \theta_c)}$$

where "S" represents substrate concentration, "X" represents biomass concentration and θ_c is solids retention time.

Obtained design equations provide the basis for dimensioning a real CMAS bioreactor as follows:

$$V = \frac{Y \cdot Q \cdot \theta_c \cdot (S_0 - S)}{(1 + k_d \cdot \theta_c) \cdot X}$$

where, Y, θ_c, k_d, predefined biomass related constants.

Considering the fact that the studied bioreactor provides aerobic treatment and therefore elimination of nitrogen based components, the parameter "dissolved oxygen requirement" is also essential design parameter [3]:

$$O_2 req = \left(\frac{Q \cdot (S_0 - S)}{f} \cdot \frac{kg}{1000\ g} \right) - 1.42 \cdot P_x + 4.57 \cdot Q \cdot (N_0 - N) \cdot \frac{kg}{1000\ g}$$

where, f - ratio BOD_5 / total BOD; N_0, N - influent / effluent ammonium ions concentration (NH_4^+).

Design of the actual CMAS bioreactor

- **Inflow rate calculation**

Considering average water consumption of nearly 150 l/P.E./d, the process inflow is determined [1]:

$$Q_0 = 150\frac{l}{PE\cdot d}\cdot\frac{5000\ C}{1000\ \frac{l}{m^3}}\ ;\qquad Q_0 = 750\ m^3/d$$

- **Determination of inlet value of BOD$_5$:**

$$inBOD_5 = 60\ \frac{g}{PE\cdot d}\cdot\frac{1000\frac{mg}{g}}{150\ \frac{l}{PE\cdot d}}\ ;$$

$$inBOD_5 = 400\ mg/l$$

- Assuming that in average nearly 30% of influent's BOD$_5$ is eliminated through the primary treatment, the influent BOD$_5$ concentration expressed as S_0, equals [4- 8]:

$$S_0 = 0.7\cdot 400\ ;\quad S_0 = 280\ mg/l$$

- **Defining of laboratory obtained biomass related constants, as presented:**

Table 1 - Biomass related constants

Biomass cell yield coefficient [mg VSS / mg BOD]	Y	0.6
Specific substrate utilization rate [(0.038 mg/l)$^{-1}$ (h)$^{-1}$ at 18°C]	q	0.038
Endogenous decay coefficient [d^{-1}]	k_d	0.07
Mean cell residence time [d]	θ_C	5
Mixed liquor suspended solids [mg/l]	MLSS	3000
Volatile suspended solids - suspended solids ratio	VSS/SS	0.333
Suspended solids [mg/l]	SS	20
VSS degradable ratio	(VSS)/VSS	0.7

- **Determining substrate concentration and BOD$_5$ in the effluent:**

$$S = \frac{1}{q\cdot Y}\cdot\left(\frac{1}{\theta_c}+k_d\right)\ ;\quad S = 12\ mg/l$$

$$effBOD_5 = S + 0.7\cdot 0.333\cdot 20\ ;$$

$$effBOD_5 = 17\ mg/l\quad (< 25 mg/l)$$

- **Dimensioning of the bioreactor - aeration tank:**

$$V = \frac{Y\cdot Q\cdot\theta_c\cdot(S_0 - S)}{(1+k_d\cdot\theta_c)\cdot X}$$

where

$$X = \frac{VSS}{SS}\cdot MLSS = 1000\ mg/l$$

$$V = 448\ m^3$$

- **Defining the hydraulic retention time θ and F/M ratio:**

$$\theta = \frac{448\ m^3}{750\ m^3/d}\cdot 24\frac{h}{d}\ ;\qquad \theta = 14.4\ h$$

$$\frac{F}{M} = \frac{(S_0 - S)\cdot Q}{X\cdot V}\ ;\qquad \frac{F}{M} = 0.45\ \frac{kg\ BOD}{kg\ MLSS\cdot d}$$

- **Calculation of Returned Activated Sludge (RAS):**

$$X_r^{'}\cdot Q_r = X^{'}\cdot(Q_r + Q)\ ;\quad X_r^{'} = \frac{10^6}{SVI} = \frac{10^6}{167}$$

$$X_r^{'} = 6000\ mg/l$$

$$X^{'} = 1.2\cdot 1000\ ;\ X^{'} = 1200\ mg/l$$

$$Q_r = 187.5\ m^3/d$$

$$R = \frac{Q_r}{Q}\ ;\quad R = 0.25$$

- **Sludge production:**

$$P_x = Y_{OBS}\cdot Q\cdot(S_0 - S)\cdot\frac{kg}{1000\ g}$$

$$Y_{OBS} = \frac{Y}{1+k_d\cdot\theta_c}\ ;\quad Y_{OBS} = 0.444$$

$$P_x = 89.33\ kg/d$$

- **Oxygen requirement of a process that provides both carbon removal and elimination of nitrogen based components:**

$$O_2req = \left(\frac{Q\cdot(S_0 - S)}{f}\cdot\frac{kg}{1000\ g}\right) - 1.42\cdot P_x + 4.57\cdot Q\cdot(N_0 - N)\cdot\frac{kg}{1000\ g}$$

$$O_2req = 344.85\ kg/d \quad ; \quad O_2req = 14.4\ kg/h$$

- **Energy consumption:**

Considering operational capacity of aerators at 70% of their standard capacity and producing of 2 kg of oxygen per kWh [1,4]:

$$Power\ reqiured = \frac{O_2req}{2 \cdot 0.7} \quad ; \quad Power\ reqiured = \frac{14.4}{0.7 \cdot 2} \cdot \frac{24\ h}{d} \cdot \frac{365\ d}{y} \cdot \frac{1}{5000\ PE}$$

$$Power\ reqiured = 18.02\ kWh/y/PE$$

4. CONCLUSION

The removal of dissolved and colloid - dispersed organic matter from wastewaters is an essential part of the modern wastewater treatment systems, where CMAS bioreactor based systems are successfully applied in numerous treatment plants. Therefore, this work produces a model of such a system that can be applied in rural wastewater treatment.

The presented studied case of a wastewater treatment system was designed as an ecological bioprocess through introduction of complex treatment procedure that integrates all basic elements of a modern bio-separation process implemented in the eco-process engineering.

Besides scientific value, obtained results from this work have also practical significance in the area of process' eco-engineering, which represents one of the main segments in the sustainable development for cleaner and healthier environment.

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IZVOD

MODELIRANJE BIOLOŠKIH REAKTORA ZA PREČIŠĆAVANJE OTPADNIH VODA

Upravljanje vodnim resursima je kompleksno pitanje, koje je od suštinske važnosti da se obezbedi uspešnost održivog razvoja u inženjerstvu zaštite životne sredine. Poznavanje savremenih procedura i separacionih procesa je ključni faktor za definisanje odgovarajućeg tretmana otpadnih voda.

Ovaj rad predstavlja uspostavljanje matematičkog modela procesa biološkog tretmana otpadnih voda. Prvi stupanj predstavlja matematičko modeliranja CMAS bioreaktora kao aeracionog rezervoara sa muljem za recirkulaciju. Drugi stupanj predstavlja praktičnu primenu matematičkih modela - dimenzionisanje pravog sistema za prečišćavanje otpadnih voda sa kapacitetom od 5.000 PE. Pri izradi glavnog projekta akcenat je stavljen na dimenzionisanje CMAS bioreaktora u cilju postizanja visoko-efikasnog uklanjanja rastvorenih organskih komponenti.

Ključne reči: *CMAS bioreaktor, matematičko modeliranje, proces dizajniranja*

Rad primljen: 15.06.2011.