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METHODICAL ASPECTS OF BIOREACTOR MODELING IN WASTEWATER MANAGEMENT

ASPEKTY METODYCZNE MODELOWANIA BIOREAKTORÓW GOSPODARKI ŚCIEKOWEJ

Abstract: Mathematical models are generally created for the needs of the processes control and for the simulations of processes occurring at the really existing objects. For the control of the bioreactors, even for multi-parameter models, it is popular to apply both calibration and application at the linear ranges of interactions. If the bioreactor runs the process based on the defined substrate with the application of the previously defined processing factor (for strains, not only species) as an effect only the determined product and the excess biomass are obtained. Also, if the process undergoes in the optimal, constant physical-chemical-biotical conditions, its mathematical description can contain the elements of not only description of transition function but also of mechanisms responsible for the process realization. A kind of bioreactor like a *n*-step municipal sewage treatment plant with the activated sewage sludge has the unidentified, multicomponent substrate, which differs both in the daily and weekly scale with the multispecies and variable composition. Also, such a bioreactor works in the wide extend of physical-chemical conditions and time-dependent inhibiting factors. Only the product - purified wastewater - is defined by standards and should have the appropriate parameters. It is clear that models with elements describing the process mechanisms have to be complicated and multifactor, thus, the nonlinear models are capable to describe not only the local and global maxima and minima, but also the extreme situations. The models sufficient for processes control and operation should only describe the transition function in the linear interaction of the process important factors (independent variables). That explains the background of the aim of the paper as a methodical assumption presentation of models describing bioreactors like sewage treatment plants with activated sludge together with the elements of the processes running in the particular facilities and calibration of such a model by biomonitoring.

Keywords: mathematical modeling of bioreactor, wastewater treatment plant, biological sewage treatment, activated sewage sludge

The system analysis, popular some times ago relying on finding the similarities between described objects being described by the same mathematical models [1] caused the development of modeling. From the simplest linear and single-parameter models, usually describing only transition function in the form of the "black box", they developed into complicated, nonlinear and multiparameter descriptions [2-10].

Application of modeling is even more practical than the system analysis. Generally, it is created for the needs of the processes control and for the simulations of processes occurring at the full-scale operating objects. For the control of the bioreactors, even for multiparameter models, it is popular to apply both calibration and application at the linear ranges of interactions [11].

If the bioreactor runs the process based on the defined substrate with the application of the previously defined processing factor (for strains, not only species) as an effect only the determined product and the excess biomass are obtained. Also, if the process is realized in the optimal, constant physical-chemical-biotical conditions, its mathematical description can contain the elements not only of the description of transition function but also the

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mechanisms responsible for process realization. So, it is possible to get the "grey box" or even the white one instead of the "black box" model.

A *n*-step municipal sewage treatment plant with the activated sewage sludge considered as a bioreactor has the unidentified, multicomponent substrate, which differs both in the daily and weekly scale with the multispecies and variable composition. Such a bioreactor works in the wide extend of physical (temperature) and chemical conditions (various and differently available sources of organic carbon, nitrogen, phosphorous and other nutrients), different variables, time dependent inhibiting factors (both allochtonic and autochtonic), biotic factors (processing factor shaped by the saprobes inflowed from sewer system and with air flux), organic loads, sludge age and contamination toxic substances [12, 13]. Only the final product - the purified wastewater - is defined by law and should have appropriate parameters.

It is clear that models with elements describing the process mechanisms have to be complicated and multifactor. Thus, the non-linear models are capable to describe not only the local and global maxima and minima, but also the extreme situations. Models sufficient for processes control and operation should only describe the transition function in the linear interaction of the process important factors (independent variables).

Bioreactor description

Bioreactors like municipal sewage treatment plants with activated sewage sludge can be considered, at least, in two separate ways. The first one is based on the possibly accurate description of the processes removing compounds of C, N, P and suspensions from the sewage. The second one is the attempt to build the tool useful in bioreactor control.

Block diagram of the biological WWTP removing C, N, P and suspension is presented in Figure 1.

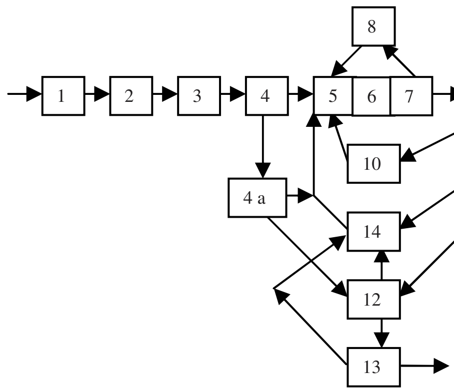

Fig. 1. Block diagram of the biological WWTP removing C, N, P and suspension, where: 1 - Measuring diffuser; 2 - Screen chamber; 3 - Grit chamber; 4 - Primary settler; 4a - Gravity thickener; 5 - Anoxic chamber; 6 - Anaerobic chamber; 7 - Aerobic chamber; 8 - Internal recirculation of NO_x-nitrogen; 9 - Final settler; 9a - Mechanical thickener; 10 - External recirculation of sewage sludge; 11 - Receiver; 12 - Anaerobic digester; 13 - Dewatering devices; 14 - Supernatants from sludge management system

The multispecies communities of both pro- and eukaryotic organisms, single and multicellular form the processing factor. Particular taxa run in the described bioreactor various functions which can be described as dependence between the biomass growth and decrease of the specific substrate [9]. For the particular taxa the substrates could be:

- Slow, medium and fast hydrolysable carbon compounds (analytically expressed as COD or BOD_5).
- Oxydable nitrogen compounds (analytically expressed as N_{NH_4} and/or $N_{NO_2^-}$ and also BOD_{NH_4}).
- Suspension $[g \cdot dm^{-3}]$ combinable from dispersed organic substance, living cells of bacteria and also the eukaryotic single and multicellular organisms.

Processing factor is consisting of the community of all the activated sludge organisms and also the immobilized exoenzymatic complex.

In the simplest case the substrate can be defined as COD and BOD_5 and the microorganisms described as total biomass. This kind of dependence can be illustrated as the one shown in the Figure 2.

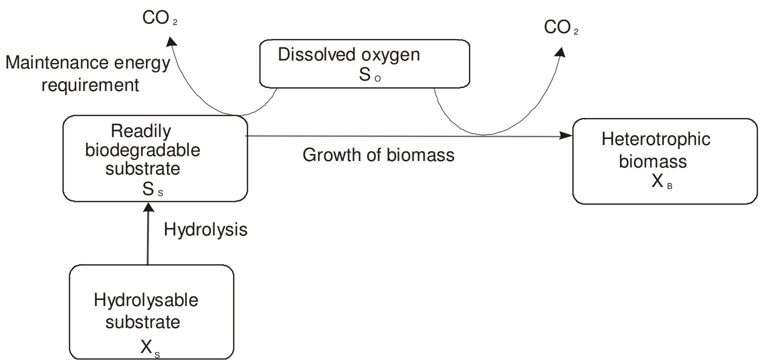

Fig. 2. Biodegradation of pollutants in biological stage of WWTP in oxygen conditions [10]

The mathematical model describing the running processes can be written as follows:

$$\frac{\partial S_O}{\partial t} = -\frac{(1-Y_H)}{Y_H}\mu_H \frac{S_S}{K_S + S_S} X_B - q_m X_B \quad (1)$$

$$\frac{\partial S_S}{\partial t} = -\frac{1}{Y_H}\mu_H \frac{S_S}{K_S + S_S} X_B - q_m X_B + k_h \frac{X_S/X_B}{K_{Xs} + X_S/X_B} X_B \quad (2)$$

$$\frac{\partial X_S}{\partial t} = -k_h \frac{X_S/X_B}{K_X + X_S/X_B} X_B \quad (3)$$

$$\frac{\partial X_B}{\partial t} = \mu_H \frac{S_S}{K_S + S_S} X_B \quad (4)$$

where: μ_H - maximum specific growth rate $[d^{-1}]$; k_h - hydrolysis rate constant $[d^{-1}]$; K_S - saturation constant for S_S $[g\ COD \cdot m^{-3}]$; K_X - saturation constant for hydrolysis $[g\ COD \cdot g\ COD^{-1}]$; q_m - maintenance energy requirement constant rate $[d^{-1}]$; S_O - dissolved oxygen concentration $[g\ O_2 \cdot m^{-3}]$; S_S - readily biodegradable substrate $[g\ COD \cdot m^{-3}]$; t - time

[d]; X_S - hydrolysable substrate [g COD·m^{-3}]; X_B - heterotrophic active biomass (summary biomass of system) [g COD·m^{-3}]; Y_H - yield constant for X_B [g COD·g COD^{-1}].

More precise models have the substrate distinguished into the particular elements (for example three fractions of carbon compounds, N_{NH_4}, N_{NO_2}, biotic and abiotic suspension exploited without hydrolysis. Also, besides oxygen N_{NO_3} and phosphorous cumulated in the biomass may be considered). Similarly, biomass elements can be separated (eg the chemoautotrophic biomass). The complete process model can contain the elements describing denitrification and dephosphatation similar to these presenting correlations between the substrate, biomass and electron acceptors [7, 9, 14].

The block diagram of the WWTP system can be presented as in the Figure below:

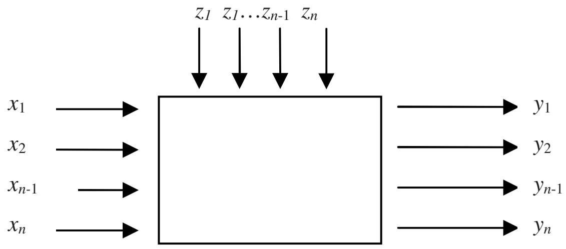

Fig. 3. Block diagram of the WWTP system, where: x_i - independent variables undergoing the intentional process control; y_i - dependent variables, process results; z_i - variables not undergoing the intentional changes, but influencing the process results

The system can be described and examined at a full range between its extremes with identification of both, local and global types of minima and maxima. It can also be described and examined for the application needs in the zone of linear dependencies where the control parameter change (x_i) and gives the proportional system reaction (y_i). System output - dependent variables - may cover, for example, suspension concentration, BOD_5 or COD value, N and P concentration. Exemplary system inputs - independent variables - may consist of: organic load, activated sludge age, external recirculation degree, internal recirculation degree, oxygen concentration, external carbon source, eventual doses of chemicals and very important, but impossible to control in full technical scale - temperature.

All the developed correlations in the range of linear dependence can be described with the following polynomial function:

for two independent variables:

$$y_i = a_0 \pm a_1 x_1 \pm a_2 x_2 \pm a_1 a_2 x_1 x_2 \qquad (5)$$

for three variables:

$$y_i = a_0 \pm a_1 x_1 \pm a_2 x_2 \pm a_3 x_3 \pm a_1 a_2 x_1 x_2 \pm a_1 a_3 x_1 x_3 \pm a_2 a_3 x_2 x_3 \pm a_1 a_2 a_3 x_1 x_2 x_3 \qquad (6)$$

etc.

Estimation of the sewage parameters

Because the linear dependences are searched, x_i can take two values (high and low), 2^n number of elements is possible, where n is the number of independent variables.

Such a model, describing only transition function in the “black box” has not the homogenous significance of all interactions. The importance of respective polynomial elements can be established after the suitable tests. Both, the model describing process mechanisms and the model enabling only quantitative transition functions should be verified and calibrated. Physicochemical parameters of inputs (x_i) and outputs (y_i) of the system should be determined. This can be achieved by the routine physical and chemical measurement and the analysis [12], but in that case only the information concerning the existing situation at the moment of sampling is available. Another analysis can be based on the communities of saprobes microfauna representatives living in wastewater treatment plant facilities. The analysis based on the structure of microfauna communities in biofilm (pecton) and also activated sludge allows to evaluate the sewage status in time of sampling and to recognize earlier incidents such as a discharge of excessive loads or substances harmful for the activated sludge. This refers to the moment preceding the sample collection at least by the species generation time with the lowest reproduction rate [15]. It suggests that, for the needs of real WWTP system control, instead of outputs (y_i), the bioindication data can be applied. It is also possible to replace the expensive and long-lasting standard procedures with the results gained by bioindication, both for validation process and the fail-safe sewage sludge processing.

Conclusion

Based on the observations presented here the following conclusions are offered:

- The local maximum and minimum of independent variables may be important in the object description.
- Models applied to the technological objects management should be calibrated and verified entirely in the area of linear interactions.
- The verification of models describing wastewater treatment with an active sludge in range of linear interactions may be conducted basing on the results of chemical and/or biological analyses.

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ASPEKTY METODYCZNE MODELOWANIA BIOREAKTORÓW GOSPODARKI ŚCIEKOWEJ

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Abstrakt: Modele matematyczne mogą być wykorzystywane na potrzeby sterowania procesami w obiektach eksploatowanych, a także do symulacji procesów poza realnie istniejącymi obiektami. Dla sterowania obiektami, takimi jak bioreaktory, praktykowane jest - nawet dla modeli wieloczynnikowych - zarówno ich kalibrowanie, jak i stosowanie w przedziałach oddziaływań liniowych. Jeżeli bioreaktor realizuje proces zdefiniowanego substratu z użyciem zdefiniowanego czynnika procesowego (zdefiniowanego dla szczepu, a nie tylko gatunku) w efekcie uzyskiwany jest ściśle określony produkt i nadmiarowa biomasa czynnika. Ponadto, jeśli proces realizowany jest w optymalnych, ustalonych warunkach fizyczno-chemiczno-biotycznych, matematyczny model procesu może zawierać w sobie elementy opisujące nie tylko funkcje przejścia, lecz również mechanizmy odpowiadające za przebieg procesu. Bioreaktor taki jak *n*-stopniowa oczyszczalnia ścieków miejskich z osadem czynnym ma niezidentyfikowany, wieloskładnikowy substrat, który jest zmienny w czasie zarówno w skali dobowej, tygodniowej, jak również rocznej. Niezdefiniowany jest również czynnik procesowy o składzie wielogatunkowym i wielorodzajowym, a często nawet wielotypowym. Ponadto bioreaktor taki pracuje w szerokim zakresie warunków fizycznych, chemicznych (różnorodne i różnie przyswajalne źródła C, N, P) oraz różnorodnych i zmiennych w czasie czynników inhibitujących. Jedynie produkt - oczyszczone ścieki - jest ustawowo definiowany i musi spełniać parametry określone w pozwoleniu wodno-prawnym. Jest zatem oczywiste, że modele zawierające elementy opisujące mechanizmy procesu muszą być rozbudowane i wieloczynnikowe (ponadto nieliniowe), jeśli mają opisywać lokalne oraz globalne maksima i minima, a także sytuacje ekstremalne. Modele przydatne dla sterowania procesami zachodzącymi w urządzeniach oczyszczalni mogą opisywać funkcje przejścia jedynie w liniowych oddziaływaniach ważnych procesowo czynników (zmiennych niezależnych). Celem opracowania jest przedstawienie zasad tworzenia modeli opisujących bioreaktor typu „oczyszczalnia z osadem czynnym" zarówno z wykorzystaniem procesów realizowanych w poszczególnych obiektach, jak i przedstawiających jedynie funkcje przejścia.

Słowa kluczowe: modelowanie matematyczne bioreaktorów, oczyszczalnie ścieków, biologiczne oczyszczanie ścieków, osad czynny