Simulation of Aerobic Granular Sludge Process Efficiency

ELENA ELISABETA MANEA, COSTEL BUMBAC*, OLGA TIRON, RAZVAN LAURENTIU DINU, VALERIU ROBERT BADESCU
National Research and Development Institute for Industrial Ecology ECOIND, 71-73 Drumul Podu Dambovitei Str.,060652, Bucharest, Romania

Using aerobic granular sludge for wastewater treatment has multiple advantages compared to conventional activated sludge systems, most important being the ability of simultaneous removal of the pollutants responsible for eutrophication: organic load, compounds of nitrogen (NH_4^+; NO_3^-) and phosphorus (PO_4^{3-}). The advantages are currently exploited for developing the next generation of wastewater treatment systems while the identified limitations are approached by experimental and theoretical researches worldwide. The aim of the study consists in evaluating the possibility of predicting the system's response to different changes in the influent wastewater loadings. The paper presents simulations results backed up by experimental data for pollutants removal efficiencies evaluation for a sequential batch reactor (SBR) with aerobic granular sludge. The mathematical model is based on the activated sludge model no. 3, which was updated by considering the simultaneous biological nitrification (NH_4^+àNO_3^-) and denitrification (NO_3^-àN_2á) processes, thus complying with the biochemical reactions occurring in aerobic granular sludge sequential batch reactors. The model developed was validated by the experimental results obtained on a laboratory scale SBR monitored for over a month.

Keywords: aerobic granular sludge, simulation, wastewater treatment

Following wastewater treatment, the discharge water quality parameters have to comply the legislation limits, the strictest and most difficult to acquire being the ones for total phosphorous and total nitrogen concentrations, with values of 2 and respectively 15 mg/L [1].

At a national scale, the biological wastewater treatment stage is based on activated sludge, removing the organic matter and, depending on the plant configuration, nutrients.

Aerobic granular sludge-based biological wastewater treatment processes [2, 3] has an important role at present due to the multiple advantages of granules when compared to activated sludge flocs, including the dense structure, improved settling properties, superior biomass concentration and higher capacity to withstand load shocks [4,5].

Obtaining a stable activated granular sludge in sequential batch reactors (SBRs) is dependent on granules selection factors (sedimentation time, percentage of total extracted volume, depth and duration of effluent discharge) [6].

Using modeling and simulation tools can provide consistent information on processes efficiencies and limitations under specific changes in the influent compounds concentration [7]. Extended studies have been focused on using simulation tools for full-scale wastewater treatment systems in order to evaluate different scenarios for increasing the treatment performances [8].

The initial simulations of aerobic granulation process were based on empirical models based on logistic curves [9] or phenomenological linear equations [10]. This category of models is mostly based on experimental results and can't be transferred to other cases without extensive adaptation according to the new conditions.

Mathematical models for simulating aerobic granular sludge evolution in SBRs for column type systems have been previously developed. One of the models encompasses three of the selection factors (effluent extraction rate, effluent extraction time and sedimentation time) at the minimum sedimentation rate of biological particles in order to evaluate the minimum sedimentation rate required for optimal aerobic granulation, considering that upper sedimentation granules are dense spheres, while low velocity values are found in small irregular granules [11]. A generalized model for determining aerobic granules sedimentation velocity was developed on the basis of Stokes' relationship and the effect of biomass concentration on sedimentation velocity [12], demonstrating the dependence of sedimentation velocity on the granular sludge volume index (SVI), average granule size and biomass concentration.

Biomass dynamics in aerobic sludge granulation in a SBR was studied using a sectoral approach [10] and the simulations results were validated on the basis of two sets of experimental results with different methods of aerobic granulation extraction. Most of the empirical models developed to quantify active sludge granulation are descriptive and cannot simulate the process in other reactors or conditions. This category of models has important limitations because it doesn't take into account factors such as the simultaneous increase of granules density and size, their decomposition due to starvation of interior biomass and biomass dimensional selection through sedimentation processes [13].

Evaluating the physical-chemical processes inside the aerobic granules is necessary due to the effect they have on compounds conversion, granules density and total amount of biomass in the system.

With regard to mass transfer, unidimensional models were developed, starting from the hypothesis that granules are isotope in terms of physical, chemical and biological properties, and the response time of aerobic granular sludge to sudden variations in negligible substrate loading [14,15].

Particles detachment rate off the granules was quantified by a model that takes into account the granules growth rate [16]. This is based on the steady state hypothesis of biofilm thickness obtained by considering a high density of the stored compounds [17].

Modeling and simulation of conversion processes focused on the particle types in the aerobic granules, the

* *email: costel.bumbac@incdecoind.ro; Phone: 0040214100377/244*

storage process, or the formation and use of microbial products.

Following the use of a modified version of the ASM3 model, there was consistency with experimental results and better transposition of microbial development. The results don't take into account either the development of polyphosphate accumulators or the storage processes of these microorganisms [15]. Simulations of biological conversion in aerobic granular sludge were also based on the unified model of extracellular polymeric substances and soluble microbial products, with the objective of quantifying the formation and use of microbial. This model, while taking into account microbial products evolution, does not show a correlation between biomass concentration and total content of extracellular polymeric substances, soluble microbial products and internally stored products [13].

Recent research on modeling and simulation of sequential aerobic granular sludge reactors mainly addresses two aspects: removing nutrients from wastewater and multiscale modeling.

Nitrogen removal modeling in aerobic granular sludge SBR performed using a model implemented in the AQUASIM program accurately predicted the conversion processes of nitrogen compounds but has the disadvantage of not considering the influence of bioreactor hydrodynamics on nitrification- denitrification [18]. Another model was developed to simulate the overall performance of granular aerobic sludge performance in the SBR system, which was implemented in the same program with valid results in effluent loading, but which did not lead to an exact quantification of microbial distribution [17].

The modeling approach based on time, size and granules grading for the overall performance of aerobic granular sludge SBR didn't take into account phosphorus removal processes. Simulations results were in good agreement with the experimental data [19, 20]. The most comprehensive developed model describes population dynamics and nutrient removal in such systems. It takes into account the spatial organization of four microbial groups (heterotrophic, ammonium and nitrite oxidizing microorganisms, polyphosphate accumulators) within each granule based on inter-species kinetic models [21].

The most important achievement so far in modeling and simulation of biological processes in sequential reactors with granular aerobic sludge is represented by a generalized model comprising the biological processes, the biological reactor hydrodynamics, the mass transfer and the diffusion [22]. The data requirements for implementing such a model are high and require permanent monitoring of the experimental installation, the characteristics of the influent, as well as of the stoichiometric and kinetic parameters [23].

The aim of the study consists in evaluating the possibility of predicting the system's response to different changes in the influent wastewater loadings. The research is based on both experimental and simulations data.

Experimental part

Materials and methods

During the experiments, a column type aerobic granular sludge SBR with a height to diameter ratio of 10 and a total working volume of 8 L was used. As can be seen in figure 1, the experimental setup consisted of: influent vessel, peristaltic feeding pump, effluent vessel and effluent withdrawal peristaltic pump. SBRs operation was ensured by a Programmable Logic Controller (PLC) which controlled the feeding pumps and air inlet and effluent outlet. The bioreactor's time sequence consisted in: anaerobic feeding (10 min.), aerobic reaction (8 h), settling (3 min.) and effluent withdrawal (5 min.).

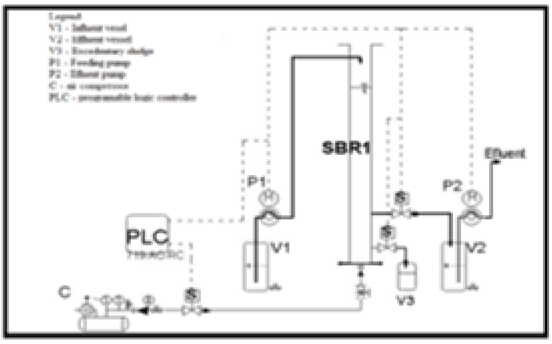

Fig. 1. Schematic representation of the aerobic granular sludge SBR [24]

The bioreactor was fed with dairy wastewater with high organic and nutrients load as shown in table 1.

Table 1
INFLUENT QUALITY PARAMETERS

Parameter	Concentration range
COD_{Cr} mg O_2/L	440-2314
BOD_5 mg O_2/L	140-843
T_P mg/L	2-19
TKN mg/L	24-165
$NH4^+$ mg/L	19-103

The treatment performances were evaluated using volumetric analyses (COD, BOD_5) and ion chromatography ICS-3000 system (NH_4^+, NO_2^- and NO_3^-).

Simulation study

The simulations were carried out by implementing the SBR characteristics and operational strategy in WEST Software, a platform for dynamic modeling and simulation of water quality systems (fig. 2).

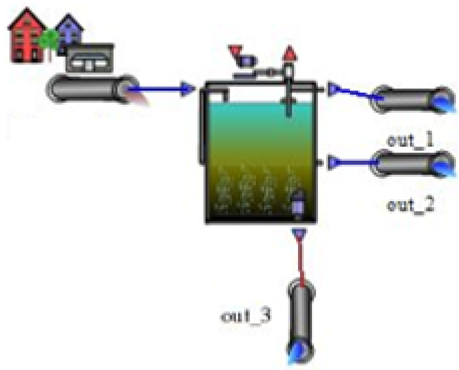

Fig. 2. WEST representation of the experimental setup

Activated sludge model number 3 (ASM3), was modified to describe the biological reactions in aerobic granular sludge SBR by adding the simultaneous storage and growth, nitrification and denitrification, following the procedure proposed by Zhou [25].

In ASM1 and ASM3 models, the total influent COD (COD_{TOT}) of the wastewater is divided into seven fractions. The most important influent COD fractions, which are used as component variables in activated sludge models, are [26, 27]:

- Ss - soluble easily degradable Ss = CODmf – Si, where CODmf – soluble COD of raw sewage microfiltrated after coagulation with zinc chloride using 0.45 μm membrane filters;

Table 2
TREATMENT PERFORMANCES

Parameter	Removal efficiencies
COD_{Cr}	90.5-99.4%
BOD_5	95.6-99.7%
T_P	47.7-79.1%
TKN	44.4-88.9%
NH_4^+	79.02-99.9%

Table 3
SIMULATION RESULTS ON EFFLUENTS CONCENTRATIONS

Parameter	Without calibration	After the model calibration
COD_{Cr} mg O_2/L	81.23	34.99
BOD_5 mg O_2/L	10.11	5.04
NTK mg/L	4.72	2.06

- Si - inert soluble 0.9û0CODeff, where CODeff – COD of the influent, filtrated using 0.45μm membrane filter;

- Xs - particulate slowly degradable COD_{BD} – Ss, where COD_{BD} = Ss + Xs – biodegradable fraction of COD; COD_{BD} = $BOD_{tot}/(1-f_{BOD})$ with the correction factor f_{BOD} = 0.15 and BOD_{tot} – total Biochemical Oxygen Demand of organic carbon compounds, assumed as 1.47 . $0BOD_5$;

- Xi - inert particulate X_{COD} – Xs, where X_{COD} = Xs + Xi – total particulate COD; X_{COD} = COD_{tot}-COD_{mf}.

Taking into account the fact that fractions nitrate- and nitrite nitrogen content in raw wastewater is below 1%, the most important TKN fractions, are [27]:

- S_{nh} - soluble ammonia nitrogen $S_{nh\ mf}$ - soluble ammonia nitrogen determined in filtrated raw wastewater samples using 0.45μm membrane filters;

- S_{nd} - soluble organic nitrogen, biologically degradable - $S_{nd} \cong 0.02 . 0S_s$;

- S_{ni} - soluble organic nitrogen, biologically undegradable - $S_{ni} = TKN_{mf} – S_{nh} – S_{nd}$, where TKN_{mf} total Kjeldahl nitrogen determined for filtrated samples using 0.45μm membrane filters;

- X_{nd} - particulate organic nitrogen, biologically degradable - $X_{nd} \cong 0.04 . 0X_s$;

- X_{ni} - particulate organic nitrogen, biologically undegradable - $X_{ni} \cong TKN_{tot} – S_{nh} – S_{nd} – X_{nd,}$ where TKN_{tot} - total Kjeldahl nitrogen in raw wastewater samples.

Results and discussions

Experimental results have shown the high efficiency of pollutants removal, with efficiencies of up to 99% (table 2).

Several simulations were carried out, while calibrating the model parameters. The model's kinetic parameters and influent fractionation coefficients were modified. Temperatures of 10, 15 and 20°C were considered. Effluent loads varied from the initial simulation case (without calibration), to the calibrated ones as can be seen in table 3, for a temperature value of 15°C.

In order to increase a model's precision and to obtain simulation results that have a high compliance degree with the experimental data, detailed and continuous monitoring are necessary. Also, in order to facilitate simulations development and their validation, a constant load synthetic wastewater should be used for the experiments. The ample changes in influent loads leads to significant changes in the aerobic granular sludge's microbial contents, phenomena that is difficult to transpose in simulations.

Conclusions

The need for increasing biological processes efficiencies is becoming more and more stringent. This, there is an increased interest in implementing aerobic granular sludge in wastewater treatment plats' biological stage, either in SBR systems, or in continuous flow reactors.

The study aimed at evaluating the treatment efficiencies of a SBR system with aerobic granular sludge, while using a high-load wastewater with ample changes in pollutants concentrations. Both the experimental and simulation results have shown that high removal rates can be acquired, with maximal values of 99.9% for NH4 $^+$, 88.9% for TKN and 99.7% for BOD_5.

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