THRESHOLDED OPERATING PARAMETERS IMPACT UPON THE BIOLOGICAL WASTEWATER TREATMENT FACILITY

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Fracțiile de recirculare şi purjă sunt responsabile pentru două dintre scalele de timp ale instalațiilor de tratare a apelor uzate, durata de staționare a reactoarelor biologice şi timpul de dublare a microorganismelor răspunzatoare pentru biodegradarea substratelor. In acest studiu au fost analizate efectele valorilor de prag impuse debitelor de recirculare şi purjă asupra performanței procesului de tratare biologică a apelor uzate. Prezența pragului este importantă afectând semnificativ comportarea şi, în consecință, performanța sistemului cu privire la procesul biologic şi eliberarea accidentală a poluanților în mediu.

The recycle and purge ratios are responsible for the two of the main time scales of the wastewater treatment facility, the residence time of the biological reactors, and the doubling time of the microorganisms accountable for the biodegradation of substrates. The effects of threshold imposed to the recirculation and purge flows upon the performance of a biological treatment process for wastewater are investigated in this study. The presence of the threshold is important, affecting significantly the behavior and, consequently, the performance of the system, with respect to the biological process and to accidental release of pollutants into environment.

Keywords: threshold, recycle ratio, purge ratio, time scale, wastewater treatment process, bioreactor, cumulative conversion

1. Introduction

The activated sludge process is the most generally applied biological wastewater treatment method (removing pollutants) for both domestic and industrial wastewaters. In such processes, organic degradation, nitrification, denitrification and other nutrients removal may take place simultaneously [1]. The activated sludge contains live (or active) biomass made of diverse microorganisms which form a complex ecological system involving reproduction, death, and predation. Also, the structure and composition of microorganism populations

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change with the transformations in the operating conditions of both the plant and in influent quality.

Waste biomass recycling is a vital part of any treatment strategy. Internal recycle is the return of the mixed liquor from the aerobic zone to the anoxic zone. External recycle is the return of sludge from the separator to anoxic zone, where the influent and sludge are mixed under anoxic conditions. The purpose of the biomass recycling from the separator to the bioreactors is to maintain its concentration or bacterial population at a desired level and increases the biomass content in the treatment basin. Biomass recycling is a method for increasing the performance of the bioreactors used in environmental pollution control, e.g. the treatment productivity of the system [2-4]. When biomass recycle is used, the time of biomass adaptation is shorter and the slow growth of some microorganisms is compensated. Thus, recycle ratio, defined as the ratio between the recycle flowrate of biomass (activated sludge) to the influent flowrate, is an important parameter in anaerobic/anoxic/aerobic wastewater treatment plant operation.

All settlements from the treatment system of wastewater generate waste biomass as a direct result of biological processes (growth and death). The excess sludge which is not recirculated is removed through the purge line [2-4].

Apart from the aforementioned effects, the recycle flow also dilutes the concentration of entering substrate and decreases the residence time of the liquid phase in the treatment basin. So the required degree of treatment can be obtained in the time interval desired. The return of activated sludge from the clarifier to the inlet of the treatment reactor is the essential feature of the process. An increasing in recirculation will increase the biomass concentration and consequently a better assimilation of the substrate by the cell can be obtained and the rate of utilization of the substrate for energetic requirements can be increased. However, the substrate removal efficiency is not enhanced by a recycle ratio larger than 80%. The sludge age can be controlled by the sludge recycle from the bottom of the clarifier [5]. Furthermore, an increase in internal recycle ratio decreases nitrate and nitrite concentration in the effluent and also improves the nitrogen removal efficiency [6].

If the amount of heterotrophic biomass in the system is independent of the recycle ratio between certain bounds because organic substrate removal is almost complete for all of those values relative to the influent, the response of the autotrophic biomass is very different and reflects the fact that the mass of autotrophic bacteria increases as the recycle ratio is increased [7].

Nitrification, the sequential transformation of ammonium to nitrate via nitrite, is typically the result of the activity of two distinct groups of autotrophic bacteria, i.e., the ammonia-oxidizing bacteria (AOBs) and nitrite-oxidizing bacteria (NOBs). As oxidation of ammonia to nitrate is a two step reaction in series, nitrite appears only when the ammonia oxidation rate is higher than the nitrite oxidation rate. A major difficulty is to maintain adequate levels of nitrifiers in the aeration bioreactors since nitrifiers grow very slowly. When the ecosystem is supplied with organic carbon, the heterotrophs compete with nitrifiers for ammonia and oxygen and are always the winner due to their faster growth rate.

Recycle of treated wastewater which mixes with the influent wastewater provides a method of balancing the hydraulic loading with the carbon loading. A partial effluent recycle increases the reactor performance too. The net effect could be an increase in the efficiency of substrate removal [8].

When major fluctuations occur at the inlet of a wastewater treatment facility, the pumping system could not adapt to the high inlet flow rates and the effect upon the biological process could be important [9]. The objective of the paper is an analysis of the effect of threshold imposed upon the recirculation and purge flows on a system of activated sludge biological treatment. These threshold values for both recycle and purge are the result of the upper limitted capacity of the pumping system.

2. The mathematical model

The system has two bioreactors in series, followed by a separator, a recycle (through which the time scale of the bioreactors is modified) and a purge, responsible for the time scale of the activated sludge.

A modified form of the ASM3 model with two-step nitrification-denitrification (ASM3-2N) [10] was used for the biological process. The system was tested using three operating time windows with data collected for two weeks: “dry weather”, “stormy weather” and “rainy weather” (http://www.benchmarkwwtp.org).

Removal of the organic matter and the nitrogen includes the organic matter elimination (carbon oxidation) by both heterotrophs and autotrophs and nitrogen consumption by autotrophic biomass. Complete nitrogen removal involves nitrification (ammonia oxidation to nitrite and subsequently to nitrate) and denitrification (nitrate transformation till nitrogen gas). In the ASM3-2N nitrification model, nitrite and nitrate dynamics is a two-step process. The autotrophic biomass is split into ammonium-oxidizers (*Nitrosomonas - AOBs*), for the first step of nitrification, and nitrite-oxidizers (*Nitrobacter - NOBs*), for the second step [9]. The slowly biodegradable substrate in wastewater is first hydrolyzed to readily biodegradable substrate by the heterotrophs. The biomass can use it for simultaneous storage and growth. When the readily biodegradable substrate is depleted (as low as the half saturation concentration) for the primary growth [11], the degradation (secondary growth) of the storage polymers takes place [12]. Denitrification is done by the facultative anaerobe biomass (heterotrophs) that can remove organic carbon through anoxic respiration on nitrite or nitrate, which both serve as electron acceptors in the absence of dissolved oxygen [9].

The process generally occurs in two steps: the biological degradation of pollutants, taking place in a series of two biological reactors (the volume of the anoxic tank is 2000 m^3 while the volume of the aerobic tank is 4000 m^3); followed by the separation of the activated sludge in a separator unit (or clarifier), in which the solids settle to the bottom [13]. Activated sludge, along with mixed liquor, is recycled from the bottom of the clarifier into the anoxic bioreactor. The aeration of aerobic tank is achieved using such mixing and inlet air flow rate so the value of $k_L a$ is 15 h^{-1}, irrespective of the inflow conditions. This value is high enough so that the process would be on the safe side with respect to the oxygen supply for all situations. It was assumed that process developed at an average temperature of 20 °C.

The sketch of the system is given in Fig. 1, with the pending notations.

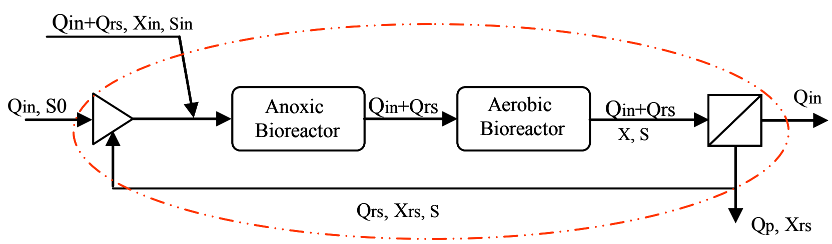

Fig. 1. The sketch of the system

The state variables of the system (*Table 1*) are divided into two categories: *soluble components*, concentrations of which are denoted by *S*, assumed to be transported by water; and *particulate components*, whose concentrations are denoted by *X*, assumed to be associated with the activated sludge concentrated in the settling tank. According to the ASM general philosophy, the unstructured COD is split into the required partitions [14]: 13% of inert soluble COD (SI), 22% of readily biodegradable COD (SS); 11% of inert particulate COD (XI) and 54% of slowly degradable COD (XS).

Table 1

Components of the model

SO_2	Dissolved Oxygen	g O_2 / m^3	**SALK**	Alkalinity	Mol HCO_3^- / m^3
SS	Readily biodegradable substrates	g COD / m^3	**XI**	Inert particulate organics	g COD / m^3
SN_2g	Dinitrogen released by denitrification	g N / m^3	**XS**	Slowly biodegradable substrates	g COD / m^3
SNH	Ammonium	g N / m^3	**XH**	Heterotrophic	g COD / m^3

4				biomass	
SNO2	Nitrite nitrogen	g N / m^3	**XSTO**	Organics stored by heterotrophs	g COD / m^3
SNO3	Nitrate nitrogen	g N / m^3	**Xns**	Nitrite-oxidizing autotrophs	g COD / m^3
SI	Soluble inert organics	g COD / m^3	**Xnb**	Ammonia-oxidizing autotrophs	g COD / m^3

The mathematical model is given by the overall and partial mass balances together with the appropriate expressions for the kinetic of different biological processes associated with the degradation of the pollutants [9].

Assuming perfect mixing, the partial mass balance for the first tank in series, the anoxic bioreactor, reads:

$$\frac{d\overline{x}_e}{dt} = \frac{Q_{in} \cdot \overline{x}_{in} + Q_{rs} \cdot \overline{x}_{rs} - \left(Q_{in} + Q_{rs}\right) \cdot \overline{x}_e}{V_{anox}} + \overline{v}_{r\_anox} \tag{5}$$

where,

- the vectors $\overline{x}_{in}$, $\overline{x}_{rs}$, $\overline{x}_e$ denote the concentrations (*g/m^3*) in the influent, Q_{in}, in the recycled sludge, Q_{rs}, and in outlet, $Q_{in} + Q_{rs}$, flows (*m^3/d*) respectively.

- $\overline{v}_{r\_anox}$ is the vector formed by the reaction rates of each component, *g/m^3·s* $v_i = \sum_j c_{ji} \cdot \rho_j$, where c_{ji} is the stoichiometric coefficient of i^{th} component in j^{th} reaction, according to the stoichiometric matrix of the model ASM3-2N, while ρ_j is the kinetic rate of j^{th} reaction, *g/m^3·s* [9] .

- V_{anox} is the volume of the anoxic bioreactor (*m^3*).

The partial mass balance for the aerobic bioreactor reads:

$$\frac{d\overline{x}}{dt} = \frac{(Qin + Qrs) \cdot (\overline{x}_e - \overline{x})}{V_{aero}} + \overline{v}_{r\_aero} \tag{6}$$

where,

- the vectors $\overline{x}_e, \overline{x}$ denote the input concentration in the reactor (*g/m^3*), $Q_{in} + Q_{rs}$, and in outlet, $Q_{in} + Q_{rs}$, flows (*m^3/d*) respectively.

- $\overline{v}_{r\_aero}$ is the vector formed by the reaction rates of each component, *g/m^3·s* $v_i = \sum_j c_{ji} \cdot \rho_j$, where c_{ji} is the stoichiometric coefficient of i^{th} component in j^{th} reaction, according to the stoichiometric matrix of the model ASM3-2N, while ρ_j is the kinetic rate of j^{th} reaction, *g/m^3·s* [9] .

- V_{aero} is the volume of the anoxic bioreactor (m^3).

In the aeration tank the mass balance for oxygen has an additional term which describes the oxygen mass transfer from the air bubbles fed through the diffusers, beside its consumption rate due to the biological process:

$$\frac{d\overline{x}}{dt} = \frac{(Qin + Qrs)\cdot(\overline{x}_e - \overline{x})}{V_{aero}} + \overline{v}_{r\_aero} + K_L a \cdot \left(SO_2^{sat} - SO_2\right) \qquad (7)$$

where,

$K_L a$ - oxygen mass transfer coefficient, d^{-1}

SO_2^{sat} - the saturation concentration of oxygen in the liquid phase, g/m^3

SO_2 - the liquid oxygen concentration, g/m^3

The recirculation and purge flows are limited by two upper threshold values. These are calculated based on average influent flow during the dry weather period:

$$y_{ave} = \frac{\int_0^{t_f} y(t)\cdot dt}{t_f} \qquad (8)$$

Applying equation (8) for the "dry weather" conditions, the calculated common values for the considered period are: Q_{in}=18445 m^3/day, COD_{in}=398.72 g/m^{3}and $NH_4{}^+{}_{in}$=31.556 g/m^3. With this constant input and for α=0.5 and β=0.005 (chosen as the middle values of the proposed ranges for the virtual experiment), threshold values for the recycling and purge flows are: Q_{rs}=9223 m^3/d and Q_p=92 m^3/d.

The influence of the recycling and purge flows, Q_{rs} and Q_p, upon the concentrations of the soluble and insoluble species in the inlet of the reactor x_{inR} is expressed in the following equations:

$$\overline{x}_{inR} = \frac{Q_{in}\cdot\overline{x}_{in}}{Q_{in} + Q_{rs}} + \frac{Q_{rs}}{Q_{in} + Q_{rs}}\cdot\overline{x}_{rs} \qquad (9)$$

For the soluble components, $\overline{x}_{rs} = \overline{x}$ (10)

and for the insoluble items. $\overline{x}_{rs} = \frac{(Q_{in} + Q_{rs})\cdot\overline{x}}{Q_{rs} + Q_p}$ (11)

In both cases, the dependency upon the system feed is the same, while that upon the recycled concentrations differs because of the effect induced by the presence of the separation unit.

3. Performance criteria

The cumulative conversion – a criterion of average performance, which takes into account the whole history of the system – was envisaged, in order to measure the fitness of the process affected by the threshold values imposed to the recirculation and purge flows [9]. The *cumulative conversion* is defined as the ratio between the amount of species *P* transformed due to the biological process from the beginning of the time window till present and the amount of species *P* fed into the system during the same interval [9].

$$\bar{X} = 1 - \frac{(1-\beta)\int_0^t Q_{in}(t) P_{out}(t)\,dt + \beta \int_0^t Q_{in}(t) P_p(t)\,dt}{\int_0^t Q_{in}(t) P_{in}(t)\,dt} \qquad (12)$$

In equation (12), P_{in} stands for the species concentration at inlet, P_{out} stands for the species concentration at outlet, while P_p stands for the species concentration at purge (see Fig. 1 for the sketch of the system).

The simulation, based upon the aforesaid mathematical model, was implemented in MATLAB using *ode15s* integration routine for stiff differential equations.

4. Results and discussions

The operating conditions and the differences between system performance in the weather conditions (dry, rain, storm) have been analyzed extensively in [9]. Preliminary runs showed that the maximum influence of the threshold is observed for rainy season. Thus, we will focus on analyzing the system performance for rainy weather conditions.

The behavior of system is intrinsically dynamic, since the operating window has an hourly variable inlet flow. The recirculation and purge flows should vary with this influent flow, according to their definitions, but, due to the upper limit of the pumping system, some threshold limits should be imposed - the maximum possible values for the recirculation and purge flows.

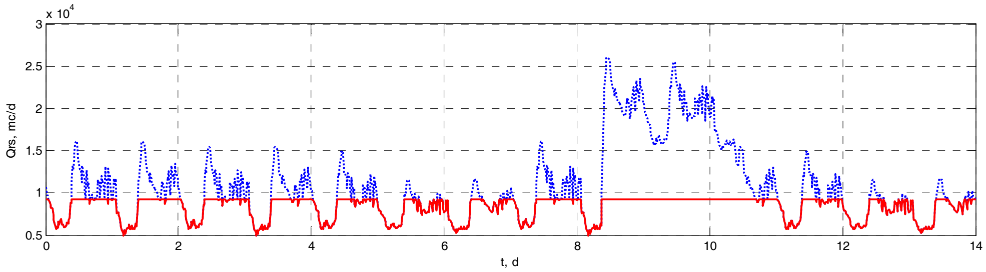

Fig. 2. The recirculation flow characteristics for the benchmark, corresponding to the rainy conditions, α=0.5 and β=0.005 (……recirculation flow "no threshold"; ___ recirculation flow with "threshold")

In Fig. 2, the dotted line profile of the graph illustrate the recirculation flow exceeds the threshold; every day, for longer or smaller intervals, counting for at least 54.05% of the total time (see Table 2) when operational parameters *α* and *β* are greater than their nominal values (*α=0.05* and *β=0.005)*.

Table 2

The relationship between the time that the thresholds for the recycled flow and the wastage sludge flow get overcome and the operational window time

α	% of total time the threshold *Qrs* gets overcame			*β*	% of total time the threshold *Qp* gets overcame		
	Dry	Rain	Storm		Dry	Rain	Storm
0.1	0	0	0	*0.001*	0	0	0
0.5	47.88	54.05	50.55	*0.005*	48.51	54.61	51.19
1.0	100	100	100	*0.01*	100	100	100

Interestingly, during the rainy period, the system works more in the "flooding conditions" than in the stormy period. The overall effect of the threshold for the recycle flow is the longer residence time of the liquid and activated sludge in the system, so that the microorganisms use better of the substrate, thus the quality of the effluent improves.

4.1. Organic removal

Municipal wastewater has, besides other constituents, a complex mixture of organic substrates. Unreacted soluble readily biodegradable substances can be discharged in the environment both by purge and by the effluent. The system performs excellent for the readily biodegradable substrates consuming them almost entirely, with values above 98% for the overall performance.

4.2. Ammonia removal

The wastewater contains a high level of ammonia and organic nitrogen. Fig. 3 shows the efficiency of ammonia removal. The overall performance of ammonium removal is better when purge flow is limited, since the residence time is higher and the wastage flow cannot remove high quantities of biomass. At high levels of recirculation ratio (Fig. 3A), the ammonium removal efficiency becomes greater than 90%, so in the case "threshold" - dotted line and "no threshold" – continue line.

Purge ratio has a greater influence on system performance conversion of ammonium. The cumulative performance of the ammonium removal has decreased continuously, when there is no limit on purge (Fig. 3B - dotted line), so that at the end of the operation it becomes less than 70%. When a maximum value for purge flow is imposed (Fig. 3B - continue line), the performance was preserved around 90%.

The activity and abundance of nitrifying bacteria in wastewater processing is critical, particularly since these organisms display low growth rate and high sensitivity to environmental disturbances and inhibitors [15]. Due to the long generation time of nitrifying bacteria and their small population growth, nitrifying bacteria usually represent < 10% of the bacterial population in the activated sludge process [16].

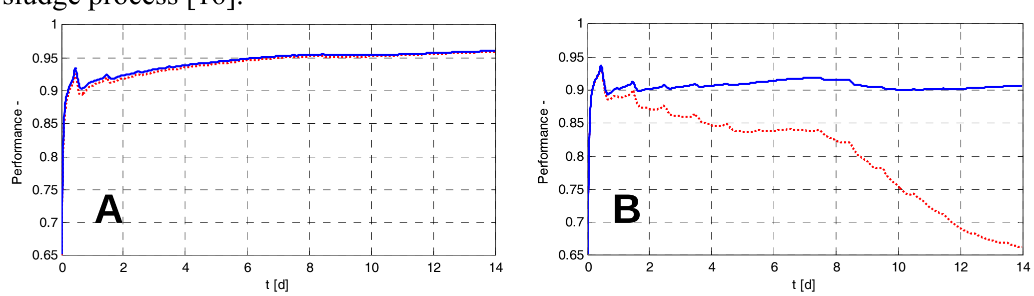

Fig. 3. Performance of the system in degrading ammonium substrate, expressed as cumulative conversion (….. "no threshold" ; __ "threshold")
A) α=1 and β=0.001; B) α=0.1 and β=0.01

Autotrophic biomass (nitrifying organisms) grows slowly compared to heterotrophs. Therefore, a long sludge retention time is required to secure the nitrification process. This fact causes excessive growth of heterotrophic biomass and accumulation of inert solids [17]. The complete nitrification of the nitrogen components produces a high level of nitrate.

In the case when threshold limits are active, a long sludge retention time causes excessive growth of heterotrophic biomass, so a better conversion of nitrate; this means that the system should perform better for smaller purge fractions.

Biomass retention is important to enhance process performances and stability [18]. Imposing a maximum purge flow increases the time scale for biomass (active and dead), and its concentration increases, more microorganisms meaning more processed substrate. Effects are observed mainly in aerobic reactor, where imposing a maximum of purge flow, the amount of remaining biomass is greater (Fig. 4 A&B&C – continue line).

In the case when there is no threshold (Fig. 4, A&B&C - dotted line), both heterotrophic and autotrophic bacteria concentrations decrease after the 8th day, when were major rainfall. From the 10th day the biomass concentration (heterotrophic and ammonium-oxidizing bacteria) starts growing while nitrite-oxidizing bacteria concentration decreases continuously. This drop leads to the population decrease and wash-out in the ultimate case. But, the number of nitrite oxidizers in a normal nitrification system with zero nitrite accumulation is at least the same magnitude or higher than the numbers of ammonia oxidizers [19]. So, when this imbalance happens, the major effect is the accumulation of nitrite, meaning the nitrification is not completely (Fig. 5A- dotted line).

The most critical factors affecting the activity and population size of nitrifying bacteria and the success of nitrification in the activated sludge process are cells residence time and temperature [16]. In activated sludge processes, relatively high cell residence times are required to establish a population of nitrifying bacteria that are capable of effective nitrification [16]. In the case when purge is thresholded, the residence time is larger, and the biomass concentration increases (Fig. 4, A&B&C - continue line), favorably affecting the process. The complete nitrification produces a high level of nitrate (Fig. 5B- continue line).

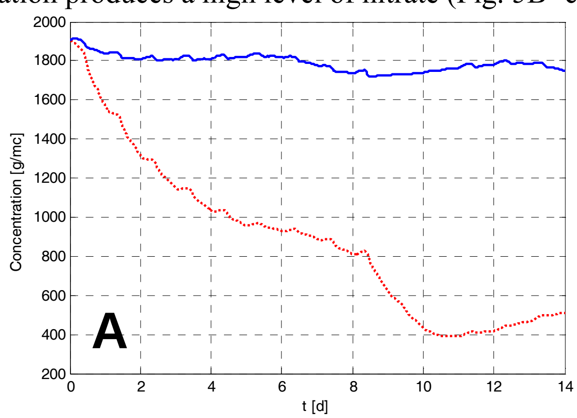

Fig. 4. Biomass concentrations in aerobic reactor for α=1 and β=0.001 (..“no threshold” ; _ “threshold”): A) Heterotrophic bacteria

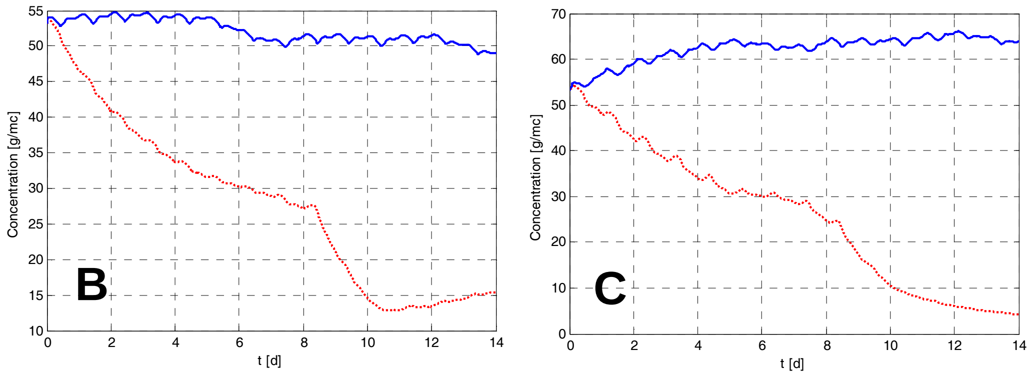

Fig. 4. Biomass concentrations in aerobic reactor for α=1 and β=0.001
(..“no threshold” ; _ “threshold”): B) Ammonium-oxidizing bacteria; C) Nitrite-oxidizing bacteria

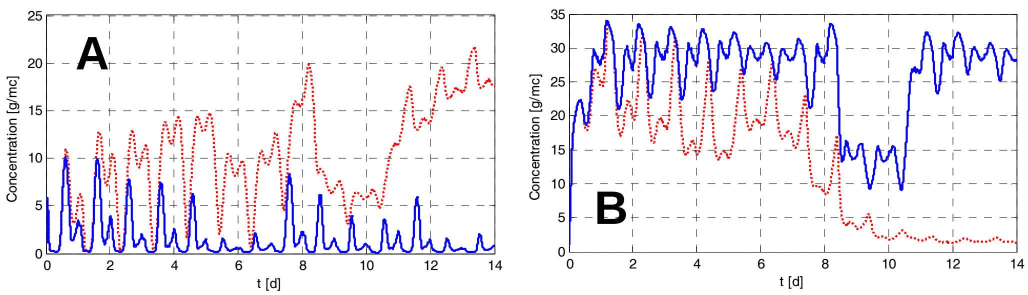

Fig. 5. Nitrite and Nitrate concentrations in aerobic reactor for α=0.1 and β=0.01
(“no threshold” ; __ “threshold”)
A) Nitrite concentration ; B) Nitrate concentration

The threshold for recirculation results in increasing the time scale of the bioreactors, thus a longer time for the biological processes to accomplish. In anoxic conditions the denitrification is carried out by numerous facultative heterotrophic bacteria. In this second process, nitrate obtained in the nitrification stage is reduced to molecular nitrogen, using the substrates contained in the wastewater as an electron donor. These steps involve the reduction of nitrate to nitrite, which is reduced of the gaseous nitrogen, that will be finally released to the atmosphere [20].

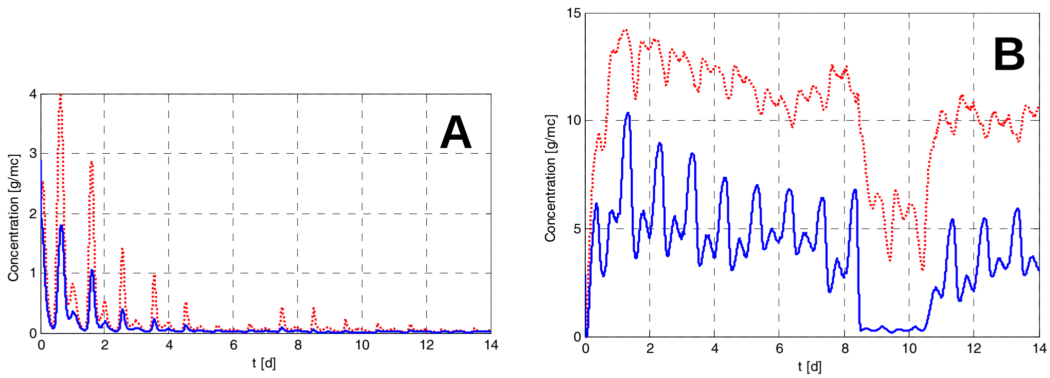

Fig. 6: Nitrite and nitrate concentrations in anoxic reactor for α=1 and β=0.001
(….. "no threshold" ; __ "threshold")
A) Nitrite concentration ; B) Nitrate concentration ;

The reduction of nitrate to nitrite and then to nitrogen gas by heterotrophic bacteria in anoxic conditions is complete. In Fig. 6, A&B observes a better conversion to nitrogen gas in the case "threshold" – continue line, to the cases of "no threshold" - dotted line. But, in the systems where the nitrified mixed liquor is recycled from the last aerobic reactor to the anoxic zone for denitrification, the nitrogen removal cannot achieve 100% because the last aerobic reactor discharges a fraction of the nitrified mixed liquor into the effluent. Thus, to be efficient these systems require a relatively high ratio of internal recycle to feed flow rates [17].

Conclusions

The present study analyzes the effects that a real life treatment facility should face when dealing with the constraints imposed by the pumping system to both recycling and purge flows. Due to its limited capacity, both flows have an upper limit, acting like a threshold – when the inflow passes a certain amount, the pumping system cannot adapt the recycling and/or the purge flows to this; instead, a fixed flow is used, till the inlet flow decreases to such values that the pumping system can deal with.

The main effect of thresholding both recycle and purge flows is, on one hand, an overall increase in the hydraulic residence time, with beneficial effects upon the time spent by the biomass in contact with the pollutants in the bioreactors, and in the other, an increase in the solid retention time, which could be beneficial with respect to the living microorganisms, but detrimental when it comes to dead cells or slowly degradable substrates, which accumulate inside the system; the recirculation and purge flows influence the bioreactors' time scales (aerobic and anoxic) together with the time scale of the biological process.

When flooded, the system has no time to properly react to this dramatic change, when the internal flows are limited by threshold values, meaning it has no time to accumulate the surplus of pollutants [9]. This, combined with the longer residence times for both liquid and solids in bioreactor, enables the system to recover faster than in the aforementioned case and re-enter its characteristic confined dynamics.

An interesting development would be to study the behavior of a slightly changed system, with a separator and recycling after each reactor, which would permit to the activated sludge from each reactor to adapt itself better to its particular operating conditions.

Acknowledgements

This work was supported at University Politehnica of Bucharest by **UEFISCSU** project No **175/1.10.2007 -** *Complex behavior of mixed microbial populations induced by time scales and segregation. Case study: wastewater biological treatment process.*

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