Searching for Efficient Operating Conditions of Wastewater Treatment Processes

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Changing the configuration of a system to treat wastewater has a major influence on the entire process, by modifying operating characteristics of system and the microbial populations involved in treatment processes. The system under study has two bioreactors in series, each followed by a separator, a recycle and a purge. Recycle and purge ratios were used from 0.1 to 1, for the former, and 0.001 to 0.01, for the latter. At the same time, the series of reactor has an external recycle, which could have a ratio from 0 to 3. The overall system performance and the diversity of the microbial communities in the reactors can be affected by working on different operating conditions. Two types of effects were investigated in this study with respect to the performance of a biological treatment process for wastewater: topological, when the configuration of the systems changes, and operational, when recycle and purge ratios change for a given topology.

Keywords*: recycle ratio, purge ratio, time scale, wastewater treatment process, bioreactor*

One of the most used techniques for wastewater treatment is biological treatment with activated sludge. Activated sludge comprises a complex microbiological community. The structure and functions of this community are determined by the nature of the wastewater treated, by concentrations of organic and inorganic nutrients [1-3], but also by the operating and environmental conditions, such as aeration intensity, solids (SRT) and hydraulic (HRT) retention times, temperature and pH, but also by system configuration [4-10].

Organic degradation, nitrification, denitrification and other nutrients removal may take place simultaneously in a biological treatment process of wastewater.

Heterotrophic organisms are responsible for the continuous degradation of organic substrate under both aerobic and anoxic. Some heterotrophic bacteria are stimulated into using nitrates and nitrites as final electron acceptors for cellular respiration in place of oxygen (denitrification), under anoxic conditions [11,12]. The electron donor is usually the organic matter.

The biological removal of soluble nitrogen components (ammonia and ammonium ions) from wastewater is a two-step process consisting of nitrification and denitrification. Nitrification is carried out by two different groups of microorganisms, the autotrophic nitrifying bacteria, which are activating in cascade, the ammonia-oxidizing bacteria (AOB) and the nitrite-oxidizing bacteria (NOB), respectively. In a nitrification process, ammonia is first oxidized into nitrite (NO_2^-) by AOB, the most important being *Nitrosomonas*, and nitrite is then oxidized to the much less toxic nitrate (NO_3^-) by NOB, of which the most important is *Nitrobacter*. Denitrification is the conversion of nitrate to nitrogen gas under anoxic conditions. One of the factors strongly influencing the efficiency of denitrification is the number of denitrifying microorganisms [13]. There is a competition for oxidizing substrates between heterotrophic bacteria and autotrophic nitrifying bacteria in the course of any biological process for wastewater treatment [14].

The activity and abundance of microbial populations in wastewater processing is critical in the design and operation of treatment systems, especially of nitrifying organisms. Particularly low growth rates of these organisms and their high sensitivity to environmental disturbances and inhibitors can curb the system performance [8].

Usually, the complex configurations for biological treatment include combinations of aerobic, anoxic and anaerobic reactors followed by a separator, and the recirculation of activated sludge between the different unit-processes. The recirculation is an important parameter, affecting the performance of entire system of wastewater treatment, being responsible for maintaining a right balance between the HRT and SRT in the system.

Waste biomass recycling is a vital part of any treatment strategy. The purpose of the biomass recycling is to maintain its concentration bacterial population at a desired level and increase the biomass content in the treatment reactors. Biomass needs a period of acclimation (adaptation) to operating and environmental conditions. By recycling biomass, the adaptation period of microorganisms to environmental conditions is shortened and it is reflected in the performance improvement [15-17]. The slow growth of some microorganisms is thus compensated. Another place where changes affect biomass is the separator (usually a settler); there is some growth here, but less important, due to the low substrate content and high biomass concentration, instead there are a lot of microorganisms dying due to substrate stress. This non-active biomass tends to accumulate into any recycle system. To prevent this, the excess sludge is removed through the purge line [15-17]. A partial effluent recycle increases the reactor performance, too. The effect could be an increase efficiency of substrate removal [18].

We studied the behavior of an improved system with two reactors, a separator and a recycling line after each reactor, which would permit to the activated sludge from each reactor to adapt itself better to its particular operating conditions. We considered the separator as an ideal unit, so the insoluble compounds or biomass are not found in the effluent.

We studied the influence upon the system efficiency of the recycle – both local and at the system level – and of the purge fractions (the local recycle fractions, α_1, α_2, and the

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α

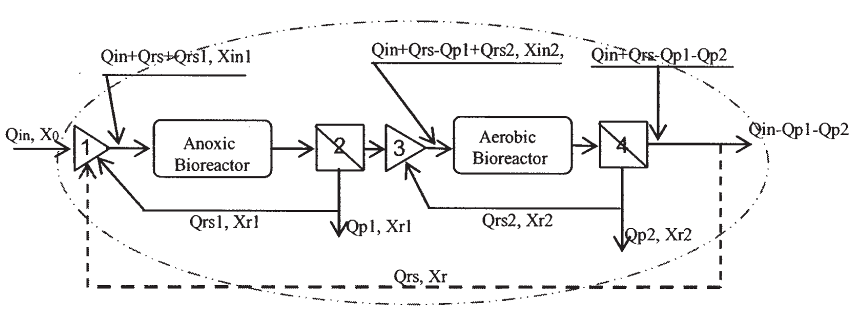

Fig. 1. The sketch of the system

Table 1
NOTATIONS USED FOR THE STATE VARIABLES DESCRIBING THE BEHAVIOUR OF THE WHOLE SYSTEM

State variables			M.U.
1	**SO_2**	Dissolved Oxygen	$g\ O_2 / m^3$
2	**SS**	Readily biodegradable substrates	$g\ COD / m^3$
3	**SN_2g**	Dinitrogen released by denitrification	$g\ N / m^3$
4	**SNH_4**	Ammonium	$g\ N / m^3$
5	**SNO_2**	Nitrite nitrogen	$g\ N / m^3$
6	**SNO_3**	Nitrate nitrogen	$g\ N / m^3$
7	**SI**	Soluble inert organics	$g\ COD / m^3$
8	**SALK**	Alkalinity	Mol HCO_3^- / m^3
9	**XI**	Inert particulate organics	$g\ COD / m^3$
10	**XS**	Slowly biodegradable substrates	$g\ COD / m^3$
11	**XH**	Heterotrophic biomass	$g\ COD / m^3$
12	**XSTO**	Organics stored by heterotrophs	$g\ COD / m^3$
13	**Xns**	Nitrite-oxidizing autotrophs	$g\ COD / m^3$
14	**Xnb**	Ammonia-oxidizing autotrophs	$g\ COD / m^3$

purge fractions, β_1, β_2, respectively the external recycle fraction, α), seen as control parameters.

The mathematical model

The system has two bioreactors in series, followed each by an ideal separator, a local recycle (through which the time scale of the bioreactors is modified) and a purge, responsible for the time scale of the activated sludge, and also an external recycle of the final effluent which is mixed with the wastewater influent.

When large fluctuations of flowrates of influent occur at the inlet of a wastewater treatment plant, the pumping system cannot adapt quickly and completely and significant effects upon biological processes may appear [19]. Due to the limited capacity of the pumping system, both recirculation and purge flows have an upper limit, acting like a threshold; instead of following the inlet flow, fixed threshold flows are used for both, till the inlet flow decreases to such values that the pumping system can adapt the recycle and purge flows. The effects of thresholding both recycle and purge flows are an overall increase of the HRT and an increase in the SRT, which could be beneficial with respect to the living micro-organisms, 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 [20]. Putting some local recycles after sedimentation introduces some supplemental degrees of freedom, which could be beneficial to the performance of the system at hand.

A modified form of the ASM3 model with two-step nitrification-denitrification (ASM3-2N) [21] was used for the biological process. The system was tested using a benchmark of three operating time windows with data collected for two weeks: “dry weather”, “stormy weather” and “rainy weather” (http://www.benchmarkwwtp.org).

In the ASM3-2N model nitrification is a two-step process – ammonia oxidation to nitrite and subsequently to nitrate. 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 [19]. 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 [22], the degradation (secondary growth) of the storage polymers takes place [23]. Denitrification (nitrate transformation till nitrogen gas) 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 [19].

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). Activated sludge, along with mixed liquor, is recycled from 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_La is 15 h^{-1}, irrespective of the inflow conditions. It was assumed that process developed at an average temperature of 20°C.

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

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 [24]: 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).

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 [19].

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

$$\frac{d\bar{x}_1}{dt}=\frac{Q_{in}\cdot\bar{x}_{in}+Q_{rs}\cdot\bar{x}_r+Q_{rs_1}\cdot\bar{x}_{r_1}-\left(Q_{in}+Q_{rs}+Q_{rs_1}\right)\cdot\bar{x}_1}{V_{anox}}+\bar{v}_{r\_anox} \quad (1)$$

where,

- the vectors $\bar{x}_{in}$, $\bar{x}_r$, $\bar{x}_{r_1}$, $\bar{x}_1$ denote the concentrations (g/m^3) in the influent, Q_{in}, in the recycled fluid mixed flow, Q_r, in the recycled sludge flow from anoxic reactor, Q_{r_1}, and in outlet, $Q_{in}+Q_r+Q_{ri}$, flows (m^3/d) respectively.

- $\bar{v}_{r\_anox}$ is the vector assembling the reaction rates of each component, $g/m^3\cdot s$

$v_i=\sum_j c_{ji}\cdot\rho_j$ 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 [19] .

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

The partial mass balance for the aerobic bioreactor reads:

$$\frac{d\bar{x}_2}{dt}=\frac{(Q_{in}+Q_r-Q_{p_1})\cdot\bar{x}_1+Q_{r_2}\cdot\bar{x}_{r_2}-(Q_{in}+Q_r-Q_{p_1}+Q_{r_2})\bar{x}_2}{V_{aero}}+\bar{v}_{r\_aero} \quad (2)$$

where:

- the vectors $\bar{x}_1$, $\bar{x}_{r_2}$ denote the input concentration in the inlet flows (g/m^3), $Q_{in}+Q_r+Q_{p1}$ and Q_{r2} respectively, while x_2 the concentration in the outlet flow, $Q_{in}+Q_r+Q_{r_2}-Q_{p_1}$, ($m^3/d$) respectively, with Q_{r2}, the recycled sludge flow from aerobic reactor, and Q_{p2}, the purge sludge flow from aerobic reactor.

- $\bar{v}_{r\_aero}$ 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_{ij} 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 [19] .

- 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:

$$\frac{d\bar{x}_2}{dt}=\frac{\left(Q_{in}+Q_r-Q_{p_1}\right)\cdot\bar{x}_1+Q_{r_2}\cdot\bar{x}_{r_2}-\left(Q_{in}+Q_r-Q_{p_1}+Q_{r_2}\right)\cdot\bar{x}_2}{V_{aero}}+\bar{v}_{r\_aero}+K_La\cdot\left(SO_2^{sat}-SO_2\right) \quad (3)$$

where,

K_La - 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:

$$y_{ave}=\frac{\int_0^{t_f}y(t)\cdot dt}{t_f} \quad (4)$$

Applying equation (8) for the “dry weather” conditions, the calculated averaged values for the considered period are: Q_{in}=18445 m^3/day, COD_{in}=398.72 g/m^3 and $NH4_{in}$=31.556 g/m^3. With these input constants 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 [20,25]. For the mixed liquor recycle the threshold value is 46115 m^3/d.

The influence of the recycling and purge flows, Q_{rs}, Q_{rs1}, Q_{rs2} and Q_{p1}, Q_{p2} upon the concentrations of the soluble and insoluble species in the inlet of the reactor x_{in1} and x_{in2} is expressed in the following equations.

For anoxic reactor:

$$\bar{x}_{in1}=\frac{Q_{in}}{Q_{in}+Q_{rs}+Q_{rs_1}}\cdot\bar{x}_{in}+\frac{Q_{rs}}{Q_{in}+Q_{rs}+Q_{rs_1}}\cdot\bar{x}_r+\frac{Q_{rs_1}}{Q_{in}+Q_{rs}+Q_{rs_1}}\cdot\bar{x}_{r_1} \quad (5)$$

For the soluble components, $\bar{x}_r=\bar{x}_2$ and $\bar{x}_{r_1}=\bar{x}_1$ (6)

and for the insoluble components

$$\bar{x}_r=0 \text{ and } \bar{x}_{r_1}=\frac{(Q_{in}+Q_{rs}+Q_{rs_1})\cdot\bar{x}_1}{Q_{rs_1}+Q_{p_1}} \quad (7)$$

For aerobic reactor:

$$\bar{x}_{in2}=\frac{Q_{in}+Q_{rs}-Q_{p_1}}{Q_{in}+Q_{rs}-Q_{p_1}+Q_{rs_2}}\cdot\bar{x}_1+\frac{Q_{rs_2}}{Q_{in}+Q_{rs}-Q_{p_1}+Q_{rs_2}}\cdot\bar{x}_{r_2} \quad (8)$$

For the soluble components, $\bar{x}_{r_2}=\bar{x}_2$ (9)

while for the insoluble components

$$\bar{x}_{r_2}=\frac{(Q_{in}+Q_{rs}-Q_{p_1}+Q_{rs_2})\cdot\bar{x}_2}{Q_{rs_2}+Q_{p_2}} \quad (10)$$

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

Performance criteria

The cumulative conversion – an averaging performance criterion, 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 [19]. 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 [19].

$$\bar{X}=1-\frac{(1-\beta_1-\beta_2)\int_0^t Q_{in}(t)P_{out}(t)\,dt+\beta_1\int_0^t Q_{in}(t)P_{p1}(t)\,dt+\beta_2\int_0^t Q_{in}(t)P_{p2}(t)\,dt}{\int_0^t Q_{in}(t)P_{in}(t)\,dt} \quad (11)$$

In equation (11), P_{in} stands for the species concentration at inlet, P_{out} stands for the species concentration at outlet, while P_{p1} and P_{p2} stands for the species concentration at purges (fig. 1 for the sketch of the system).

The simulations, based upon the aforesaid mathematical model, were done in MATLAB using *ode15s* integration routine for stiff differential equations.

Results and discussions

Considering the average of the influent flow and input concentrations we chose as the middle values of the proposed ranges $\alpha_i = 0.5$ and $\beta_j = 0.005$, i, j $\in$ {1, 2} and $\alpha \in$ [0.3]we analyzed the performance obtained for the steady-state conditions, in comparison with the system in which there is only one separator and the sludge is recycled from the outlet to the first reactor (recycle ratio is a = 0.5 and purge ratio b = 0.005) (table 2) [20].

When the external recirculation is absent, the liquid subjected to nitrification is not returning in the system so the denitrification does not occur. As such, all the products of nitrification, nitrite and nitrate, are released into the discharge.

The concentration of readily biodegradable substrate decreases in anoxic reactor when external recirculation flow increases. This decrease is affecting the denitrification rate, which depends on carbon availability [26]. Readily biodegradable substrate is a product of hydrolysis of slowly biodegradable substrate. Heterotrophic bacteria are responsible for hydrolysis of particulate substrates and can metabolize all degradable organic substrates. Yet, the accumulation of inert materials and slowly biodegradable substrate is high, especially in the anoxic reactor due to the same local recycling.

The hydrolysis process is significantly slower than heterotrophs growth. Therefore, it is assumed to be the rate limiting step for the utilization of the slowly biodegradable substrate [27]. But also denitrification is slow when the slowly biodegradable substrate is present in high concentration. In aerobic reactor the concentration of slowly biodegradable substrate is zero because the ASM3-2N model assumes that XS enters the system only through influent. Both nitrite and nitrate concentrations are greater than in the original configuration.

When external recirculation ratio is highest, the nitrate concentration in anoxic reactor increased. So the denitrification efficiency in removing the nitrate will be limited by the recycle ratio [28].

Denitrification occurs by facultative heterotrophic microorganisms which uses nitrate as terminal electron acceptor in its respiration process, in the absence of oxygen. The dissolved oxygen has a major effect on the denitrification process [29,30]. The initial nitrate concentration in the anoxic zone influences the denitrification rate, which depends on the concentrations of readily biodegradable substrate, the absence of dissolved oxygen and the concentration of nitrate [26,31]. In this configuration, the dissolved oxygen concentration is high.

The biomass concentration is very low compared with the system with a single separator. The wastewater characteristics and process operating conditions, such as nitrogen concentration increase in loading feed or sudden dissolved oxygen concentration variation (due to increased loading), affect the structure and abundance of bacterial population and therefore the oxidation rates of substrates.

But if the purge ratio is reduced and as such, the amount of sludge removed, the autotrophs concentration becomes higher thus the values obtained for ammonium and nitrite are lower in aerobic reactor; however, the slowly biodegradable substrate accumulation is very high in the anoxic reactor (table 3).

We tested the system in dynamic conditions for a period of 14 days in rainy weather, using the data collected in the benchmark input files and the process sizing reported in this study (http://www.benchmarkwwtp.org). We compared the results with those obtained in the system with a single separator. We studied the removal efficiency

Table 2

STEADY STATE VALUES OF THE STATE VARIABLES FOR THE TWO BIOREACTORS CORRESPONDING TO THE PSEUDO-INLET CONDITIONS RESULTED FROM AVERAGING THE DRY WEATHER BENCHMARK INPUT ; FOR CASE WITH 3 RECYCLE, THE RECIRCULATION EXTERNAL FRACTION (α) VARIES

Parameter	Values, g/m^3 **1 recircycle** **1 purge** a = 0.5 ; b = 0.005		Values, g/m^3 **3 recycle + 2 purge** α =0 α1 = α2 = 0.5 ; β1 = β2 = 0.005		Values, g/m^3 **3 recycle + 2 purge** α =1 α1 = α2 = 0.5 ; β1 = β2 = 0.005		Values, g/m^3 **3 recycle + 2 purge** α =3 α1 = α2 = 0.5 ; β1 = β2 = 0.005	
	anox	*aero*	*anox*	*aero*	*anox*	*aero*	*anox*	*aero*
organic substrate easy biodegradable, SS	**43.32**	**0.085**	82.82	0.13	**41.5**	0.17	23.85	0.26
soluble inert organic materials, SI	**48.94**		48.94		48.94		48.94	
slowly biodegradable substrate, XS	**268.97**	**190.1**	13722.64	0	8233.6	0	5146.01	0
particulate inert material, XI	**4011.28**	**4023.44**	2795.36	408.7	**1677.2**	181.7	1048.26	78.93
ammonium nitrogen, NH_4	**22.75**	**0.53**	30.14	0.53	**15.47**	0.8	9.55	1.32
gaseous organic nitrogen, N_2	**7.81**		0		**0**		0	
nitrite, NO_2	**0.019**	**0.106**	0	0.1	0.078	0.15	0.2	0.28
nitrate, NO_3	**3.84**	**27.11**	0	30.28	14.8	29.6	20.5	28.7
dissolved oxygen, O_2	**1.63**	**4.91**	0	6.6	3.35	6.71	4.88	6.83
HET (heterotrophs)	**4164.34**	**4204.91**	$2.2*10^{-4}$	1254.2	$8.5*10^{-7}$	937.4	$1.2*10^{-12}$	651.67
AOB (*Nitrosomonas*)	**128.92**	**130.21**	$6*10^{-5}$	111.7	$5.8*10^{-9}$	80.3	$1.1*10^{-14}$	56.03
NOB (*Nitrobacter*)	**172.85**	**174.71**	$6*10^{-5}$	155.9	$3.3*10^{-9}$	111.9	$8.5*10^{-15}$	77.68

Table 3

STEADY STATE VALUES OF THE STATE VARIABLES FOR THE TWO BIOREACTORS CORRESPONDING TO THE PSEUDO-INLET CONDITIONS RESULTED FROM AVERAGING THE DRY WEATHER BENCHMARK INPUT ; FOR CASE WITH 3 RECYCLE, THE RECIRCULATION EXTERNAL FRACTIA(α) VARIES AND PURGE RATIO IS MINIMAL

Parameter	Values, g/m^3 **1 recircycle** **1 purge** a = 0.5 ; b = 0.005		Values, g/m^3 **3 recycle + 2 purge** α =0 α1 = α2 = 0.5 ; β1 = β2 = 0.001		Values, g/m^3 **3 recycle + 2 purge** α =3 α1 = α2 = 0.5 ; β1 = β2 = 0.001	
	anox	*aero*	*anox*	*aero*	*anox*	*aero*
organic substrate easy biodegradable, SS	**43.32**	**0.085**	105.45	0.07	**23.8**	0.1
soluble inert organic materials, SI	**48.94**		48.94		48.94	
slowly biodegradable substrate, XS	**268.97**	**190.1**	44620.4	0	25281.1	0
particulate inert material, XI	**4011.28**	**4023.44**	13370.2	5482.9	5186.38	**1080.8**
ammonium nitrogen, NH_4	**22.75**	**0.53**	30.36	**0.26**	**8.88**	**0.37**
gaseous organic nitrogen, N_2	**7.81**		0		$9*10^{-4}$	
nitrite, NO_2	**0.019**	**0.106**	0	**0.049**	0.049	**0.069**
nitrate, NO_3	**3.84**	**27.11**	0	32.59	22.0	30.9
dissolved oxygen, O_2	**1.63**	**4.91**	0	5.99	4.6	6.46
HET (heterotrophs)	**4164.34**	**4204.91**	69.44	2716.89	0.89	1615.5
AOB (*Nitrosomonas*)	**128.92**	**130.21**	1.93	218.7	$7.2*10^{-3}$	153.16
NOB (*Nitrobacter*)	**172.85**	**174.71**	1.94	305.8	$4.1*10^{-3}$	213.95

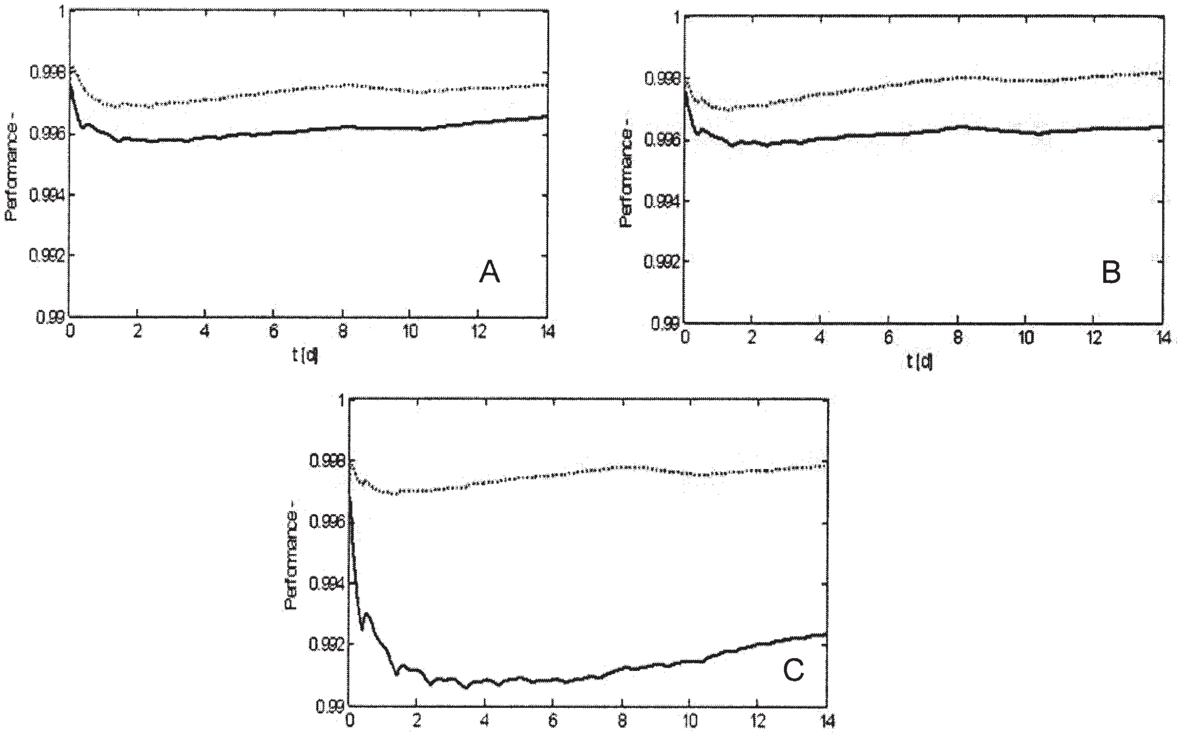

Fig. 2. Performance of the system in degrading for readily biodegradable substrate, expressed as cumulative conversion (… "system with 1 recycle" ; __ "system with 3 recycles"): α=1
A) a =0.1 and b = 0.001; $\alpha_1 = \alpha_2 = 0.1$ and $\beta_1 = \beta_2 = 0.001$;
B) a =0.5 and b = 0.001; $\alpha_1 = \alpha_2 = 0.5$ and $\beta_1 = \beta_2 = 0.001$;
C) a =0.5 and b = 0.005; $\alpha_1 = \alpha_2 = 0.5$ and $\beta_1 = \beta_2 = 0.005$

of organic substrates, rapidly and slowly biodegradable and ammonium-nitrogen. We considered three options for internal recycling and purge ratios. Analyzing the results obtained in stationary conditions showed that better results were obtained for external recycling ratio equal to 1. The values for the internal recirculation and purge fractions are: a, $\alpha_1, \alpha_2 \in$,{0.1, 0.5} and b, $\beta_1, \beta_2 \in$,{0.001, 0.005} The recycling and purge ratios influence two of the time scales of the biological reactors: the residence time which is mainly influenced by the recycling ratio and the doubling time of the biological process, which is influenced by the purge fraction [19].

The figure 2 (A, B, C) shows the efficiency of readily biodegradable substrates removal. Even if the overall performance of readily biodegradable substrates removal is better when system has a single separator, even in this configuration the removal rate is over 90%. Lower values were obtained for the highest values of the purge (b = β_1 = β_2 = 0.005, fig. 2C).

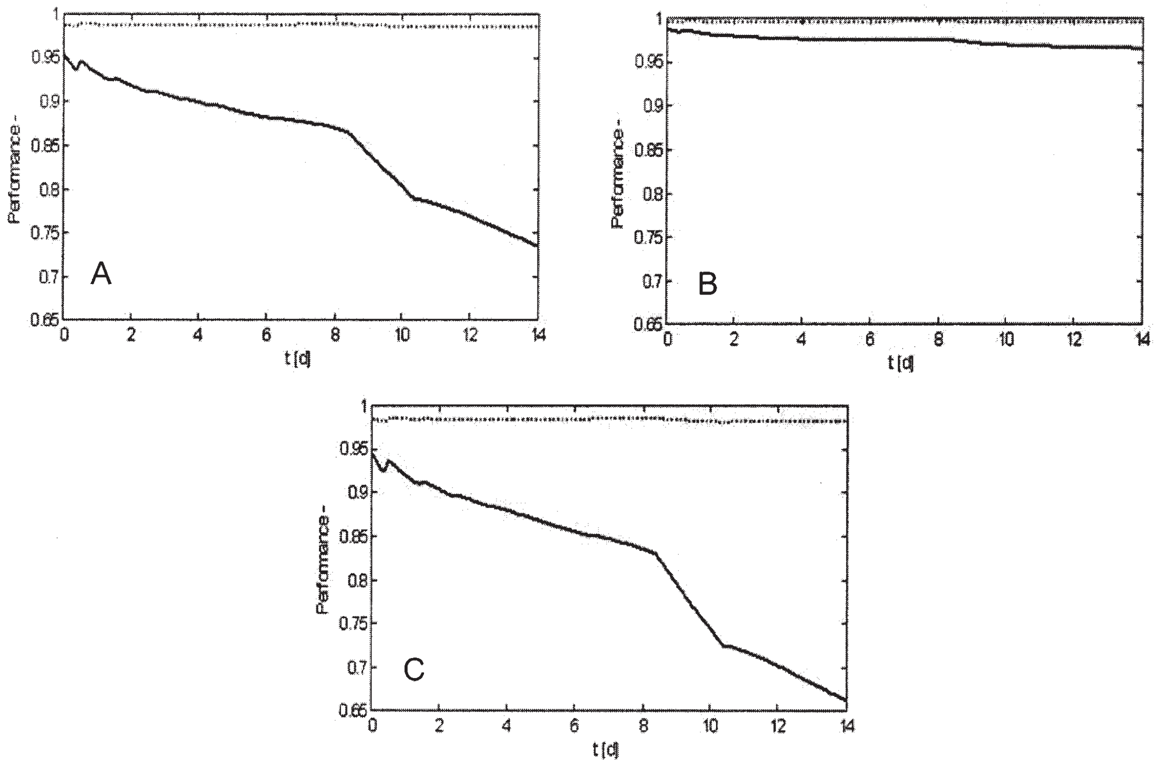

Fig. 3. Performance of the system in degrading for slowly biodegradable substrate, expressed as cumulative conversion (… “system with 1 recycle” ; __ “system with 3 recycles”): α=1. A) a =0.1 and b = 0.001; $\alpha_1 = \alpha_2 = 0.1$ and $\beta_1 = \beta_2 = 0.001$; B) a =0.5 and b = 0.001; $\alpha_1 = \alpha_2 = 0.5$ and $\beta_1 = \beta_2 = 0.001$; C) a =0.5 and b = 0.005; $\alpha_1 = \alpha_2 = 0.5$ and $\beta_1 = \beta_2 = 0.005$=1

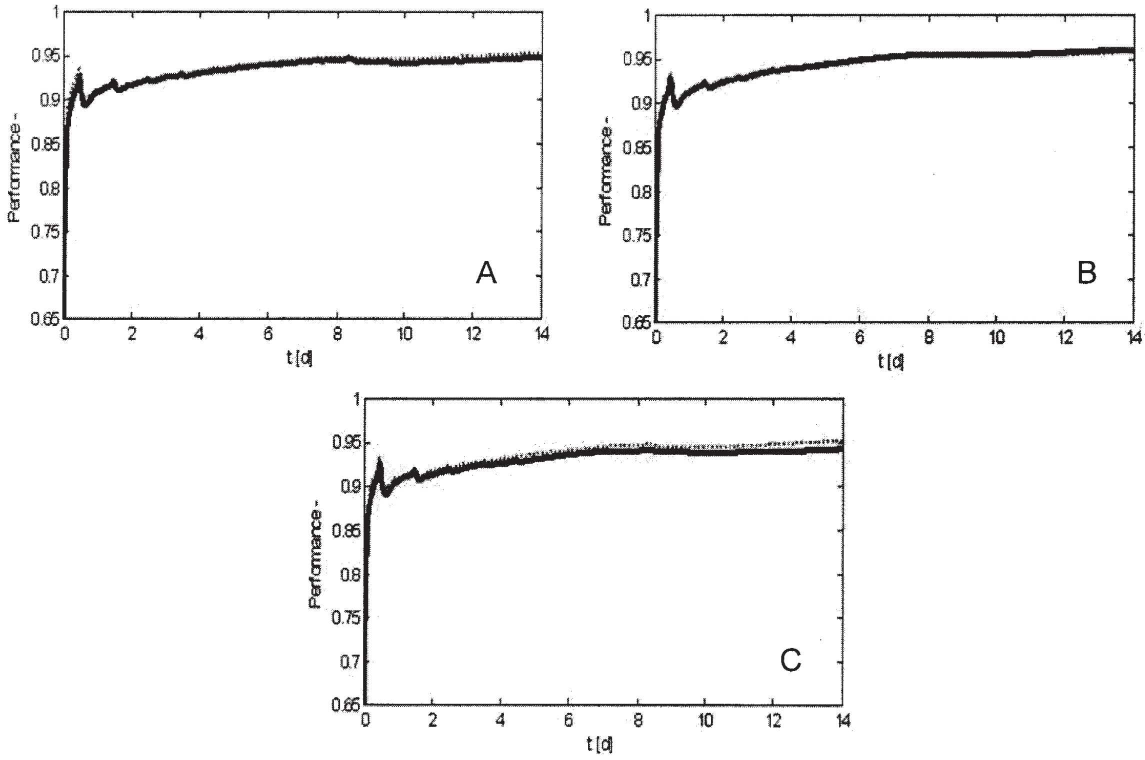

Fig. 4. Performance of the system for ammonium substrate removal, expressed as cumulative conversion (… “system with 1 recycle” ; __ “system with 3 recycles”): α=1. A) a =0.1 and b = 0.001; $\alpha_1 = \alpha_2 = 0.1$ and $\beta_1 = \beta_2 = 0.001$; B) a =0.5 and b = 0.001; $\alpha_1 = \alpha_2 = 0.5$ and $\beta_1 = \beta_2 = 0.001$; C) a =0.5 and b = 0.005; $\alpha_1 = \alpha_2 = 0.5$ and $\beta_1 = \beta_2 = 0.005$

For slowly biodegradable substrate, the performances are different (fig. 3 – A, B, C). If for the base values (0.5) of the recirculation fractions and the minimum values (0.001) of the purge fractions the removal of slowly biodegradable substrates is over 90% (fig. 3-B), for the minimum (0.1 and 0.001, respectively) and the base (0.5 and 0.005) values of recycling and purge ratios – (fig. 3-A) for the former, and (fig. 3-C) for the latter – the performance of system is below 70%. The accumulation of slowly biodegradable substrates occurs in anoxic reactor, the first reactor from system. In ASM3 models all slowly biodegradable substrates are contained in the wastewater influent and none is generated in decay processes [24]. The slowly biodegradable substrate is broken down to soluble, readily biodegradable compounds by hydrolysis. The rate of hydrolysis is much lower than the rate of utilization of hydrolysis products used for the biosynthesis of heterotrophic bacteria.

For the same value of purge ratios ($b = \beta_1 = \beta_2 = 0.001$), the removal of the slowly biodegradable substrates increased with the increase of the recycled sludge ratio (fig. 3 – A and B). When the same values for the recirculation ratios were kept the same, but the purge fractions increased, the performance worsened (fig. 3 – B and C).

The effect of recirculation and purge ratios on nitrogen removal is rather low, the results showing this little impact on system performance (fig. 4 – A, B, C), irrespective of the other operating parameters values.

Conclusions

We analyzed the effects induced by changing the configuration of a system of biological treatment of wastewater and by the variation of the recycling and purge ratios upon the system performance. The system with separator and recycle after each reactor, which permits to the activated sludge to adapt itself better to the particular operating conditions of each bioreactor, showed a good removal efficiency of ammonium, at the expense of accumulation of organic substrates (slowly biodegradable substrates). This may influence both the sludge characteristics (the metabolism and structure bacterial population) and the quality of effluent. At the same time, the production of excess sludge is affected, proving once more that this is one of the most serious challenges in biological wastewater treatment.

Notations

– System with two separators
  α - external recirculation ratio
  α_i - recirculation ratio, i ε {1, 2}
  $\alpha\beta_j$ - purge ratio, j ε {1, 2}
– System with one separators
  a – recirculation ratio
  b – purge ratio
Q_{rs} - recirculation flow
Q_{in} – feeding flow
K_La – Oxygen mass transfer coefficient [h^{-1}]
COD – Chemical Oxygen Demand [g O_2 /m^3]
ASM – Activated Sludge Model
HRT - Hydraulic Retention Time
SRT - Solids Retention Time

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.

References

1. MATZ, C.; JÜRGENS, K. Microbial Ecology, **45**(4),2003, p. 384
2. JEFFERSON, B.; BURGESS, J.E.; PICHON, A.; HARKNESS, J.; JUDD, S.J. Water Research, **35**(11),2001, p. 2702
3. EGLI, T.; ZINN, M. Biotechnology Advances, **22**(1-2),2003, p. 35-43
4. LÓPEZ-VÁZQUEZ, C.M.; HOOIJMANS, C.M.; BRDJANOVIC, D.; GIJZEN, H.J.; VAN LOOSDRECHT, M.C.M. Water Research, **42**(10-11),2008, p. 2349
5. HENZE, M.; ASPEGREN, H.; LA COUR JANSEN, J.; NIELSEN, P.H.; LEE, N. water Science and Technology, **45**(6),2002, p. 137
6. LISHMAN, L.A.; LEGGE, R.L.; FARQUHAR, G.J. Water Research, **34**(8),2000, p. 2263
7. TECK, H.C.; LOONG, K.S.; SUN, D.D.; LECKIE, J.O. Desalination, **245**(1-3),2009, p. 28
8. HU, J.; LI, D.; LIU, Q.; TAO, Y.; HE, X.; WANG, X.; LI, X.; GAO, P. Journal of Environmental Sciences, **21**(3),2009, p. 387
9. LAVRIC, V.; GRAHAM, D.W. Journal of Theoretical Biology, **264**(1),2010, p. 45-54
10. PARK, H.-D.; NOGUERA, D.R. Water Research, **38**(14-15),2004, p. 3275
11. MOUSSA, M.S.; HOOIJMANS, C.M.; LUBBERDING, H.J.; GIJZEN, H.J.; VAN LOOSDRECHT, M.C.M. Water Research, **39**(20),2005, p. 5080
12. CHUANG, S.-H.; OUYANG, C.-F. Water Research, **34**(8),2000, p. 2283
13. NAIR, R.R.; DHAMOLE, P.B.; LELE, S.S.; D'SOUZA, S.F. Chemosphere, **67**(8),2007, p. 1612
14. ELENTER, D.; MILFERSTEDT, K.; ZHANG, W.; HAUSNER, M.; MORGENROTH, E. Water Research, **41**(20),2007, p. 4657
15. NOÜE, J.D.L.; EIDHIN, D.N., 1988; Vol. 31
16. PEREIRA, A.; MOTA, M.; ALVES, M. Water Environment Research, **73**(2001, p. 612-621
17. HWU, C.S.; VAN BEEK, B.; VAN LIER, J.B.; LETTINGA, G. Biotechnology Letters, **19**(5),1997, p. 453
18. YOOCHATCHAVAL, W., OHASHI, A., HARADA, H., YAMAGUCHI, T.; SYUTSUBO, K. International Journal of Environmental Research, **2**(3),2008, p. 231
19. STOENICA, M.; LAVRIC, V. Rev. Chim. (Bucharest), **61**, no. 4, 2010, p. 407
20. STOENICA, M.; LAVRIC, V. U.P.B. Sci. Bull., Series B, , **In Press**(2009,
21. IACOPOZZI, I.; INNOCENTI, V.; MARSILI-LIBELLI, S., GIUSTI, E. Environmental Modelling & Software, **22**(6),2007, p. 847
22. SIRIPONG, S.; RITTMANN, B.E. Water Research, **41**, no. 5,2007, p. 1110
23. NI, B.-J.; YU, H.-Q. Chemical Engineering Journal, **140**(1-3),2008, p. 101
24. HENZE, M.; GUJER, W.; MINO, T. Activated sludge models ASM1, ASM2, ASM2d and ASM3. IWA Scientific and Technical Report no. 9, 2000
25. STOENICA, M.; LAVRIC, V. Chemistry Magazine,2009
26. KOMOROWSKA-KAUFMAN, M.; MAJCHEREK, H.; KLACZYNSKI, E. Process Biochemistry, **41**(5),2006, p. 1015
27. ORHON, D.; COKGOR, E.U.; SOZEN, S. Water Science and Technology, **39**(1),1999, p. 87
28. SOZEN, S.; ARTAN, N.; ORHON, D.; AVCIOGLU, E. Water Science and Technology, **46**(9),2002, p. 237
29. PLÓSZ, B.G.; JOBBÁGY, A.; GRADY, C.P.L. Water Research, **37**(4),2003, p. 853
30. SHEN, J.; HE, R.; HAN, W.; SUN, X.; LI, J.; WANG, L. Journal of Hazardous Materials, **172**(2-3),2009, p. 595
31. CHOUBERT, J.-M.; MARQUOT, A.; STRICKER, A.-E.; RACAULT, Y.; GILLOT, S.; HEDUIT, A. Water SA, **35**(1),2009

Manuscript received: 22.06.2010