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Simulation of Substrate Removal in Step-Feed Process with Model ASM1

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Abstract. Based on Activated Sludge Model NO.1 (ASM1) in wastewater treatment plant (WWTP), the models of single-feed and step-feed process were established. The components removals in two types of feed processes were simulated by Matlab Simulink. The results show that organic matter removal and heterotrophic organisms growing can benefit from single-feed process, while the step-feed process will promote ammonia nitrogen removal and autotrophic organisms (X_{BA}) growing. Simulation shows that the increment of X_{BA} in step-feed process can be 0.4% higher than that in single-feed. The oxygen uptake rate of nitrification (NOUR) in WWTP shows that the step-feed process can effectively upgrade the NOUR which X_{BA} can reach to 695 $mgO_2/(L \cdot d)$, 1.96 times higher than the average value of another 4 WWTPs with single-feed process.

Introduction

Both the step-feed process in the municipal wastewater treatment plants (WWTP), such as ECOSUNIDE process [1,2], and the lab devices demonstrate better effects on dephosphorization and denitrification [3]. However, due to long-term process of activated sludge test and various interference factors, it is difficult to have the same experimental conditions for comparison in different lab tests. Meanwhile, as organics from the effluent of aerobic tanks could be absorbed by activated sludge, the organic concentration after sedimentation can hardly describe the actual transformation process of organics [4]. Therefore, the normal activated sludge test is not available to observe the slight changes during the process of substrate removal and biomass growth, including the slow accumulation of autotrophic bacteria (X_{BA}) growth and heterotrophic organisms (X_{BH}).

Activated sludge models (ASMs) recommended by International Water Association(IWA) is a widely accepted model, in which ASM1 can simulate the process of the removal of organics and ammonia-nitrogen (S_{NH}) in WWTPs successfully [5]. In this research, by setting the same initial biomass and influent components, the model ASM1 was adopted to simulate the changes of organics and S_{NH} in the step-feed and single-feed process respectively. And we can further discuss the characters of substrate removal in two different processes.

Modeling and Method

The system in which the influent running into aerobic tank from inlet A in Fig.1 and then flow to other aerobic tanks successively is called single-feed process, while the system in which influent running into aerobic tank from different inlets A-D in Fig. 1 is called step-feed process. It can be considered that both systems are composed of several completely mixed tanks in series.

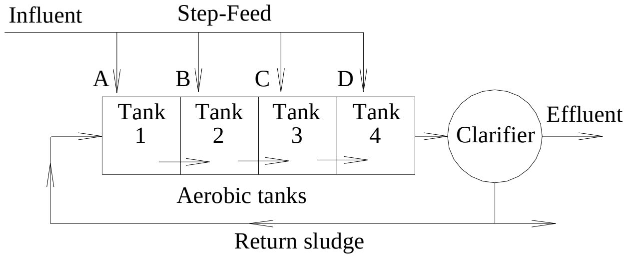

Fig. 1 Step-feed process

There is no internal recycle, all biochemical reactions, including substrate removal, growth and decay of the heterotrophic and autotrophic bacteria, take place in the aeration basin only. Therefore, only carbonization of organics and nitrification of S_{NH} in the aerobic tanks are included in the simulation.

Components in the model include: readily biodegradable organic (S_S), slowly biodegradable organic (X_S), S_{NH}, X_{BA}, X_{BH} and dissolved oxygen (S_O). When the system becomes steady-state mixed, the differential equation of components in Tank can be written as follows:

$$\frac{dC_{ki}}{dt} = (C_{k,outi-1}Q_{outi-1} + C_{k,inlet}Q_{in\_i})\frac{1}{V_i} - C_{ki}(Q_{outi})\frac{1}{V_i} + r_k \qquad (1)$$

i=1,2， 3， 4， (i the number of the tank)

For dissolved oxygen, an oxygen input item $K_{LA}\times S_O$ is needed in the both equations. The stoichiometry matrix and kinetics for simplified ASM1 are presented in Table 1[6].

Table 1 Stoichiometry matrix for simplified ASM1

Component i / Process j	1 S_S	2 X_S	3 X_{BH}	4 X_{BA}	5 S_O	6 S_{NH}	Process rate ρ_j
Aerobic growth of X_{BH}	$-1/Y_H$	-	1	-	$-(1-Y_H)/Y_H$	$-i_{XB}$	ρ_1
Aerobic growth of X_{BA}	-	-	-	1	$-(4.57-Y_A)/Y_A$	$-i_{XB}-1/Y_A$	ρ_2
Decay of X_{BH}	-	$1-f_p$	-1	-	-	-	ρ_3
Decay of X_{BA}	-	$1-f_p$	-	-1	-	-	ρ_4
Hydrolysis	1	-1	-	-	-	-	ρ_5
Transfer rate equation	$r_k = \sum_j v_{ij} r_j$						

Note: $r_1 = m_H \frac{S_S}{K_S + S_S}\frac{S_O}{K_{O,H} + S_O} X_{B,H}$; $r_2 = m_A \frac{S_{NH}}{K_{NH} + S_{NH}}\frac{S_O}{K_{O,A} + S_O} X_{B,A}$ $r_3 = b_H X_{B,H}$;

$r_4 = b_A X_{B,A}$; $r_5 = k_h \frac{X_S / X_{B,H}}{K_X + X_S / X_{B,H}}\frac{S_O}{K_{O,H} + S_O} X_{B,H}$

It is assumed that the influent ratios for four inlets are 25% and all aerobic tank with the same volume [7]. The dimension of tank and components of influent are shown in Table 2[8]. Because of four inlets, six components in each tank have six differential equations of the process, there have 24 differential equations in the whole aerobic tanks. Using the program module developed by Matlab Simulink(R2009a), the numerical solution of differential equations can be resolved. By setting the same initial conditions and parameters as well as the different ratio of step-feeding, both single-feed and step-feed processes can be simulated.

Table 2 Initial conditions for simulation

Flow rate [m^3/d]	Total volume of tanks [m^3]	Ratio of return sludge	S_S [mg/L]	X_S [mg/L]	S_{NH} [mg/L]	X_{BH} [mgCOD/L]	X_{BA} [mgCOD/L]
50000	20000	0.8	50	110	40	1800	100

Results and Discussion

Changes of X_S, S_S and X_{BH}. In step feed, the flow rates through tanks are fairly different with single feed. Hence it is not appropriate to compare the effluent concentrations for all the tanks. However, since Tank 4 always remains the same flow rate, we could use the component concentrations of effluent from the Tank 4, in Fig.2, to judge the merits and demerits of the different process.

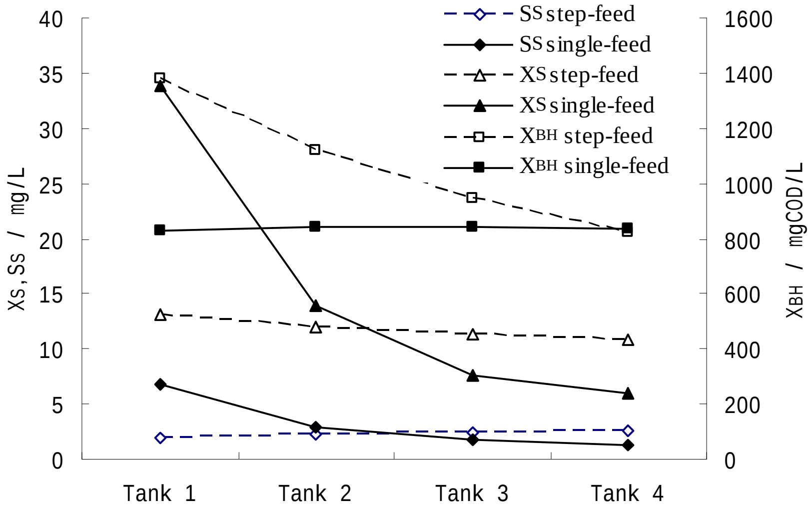

Fig. 2 Changes of S_S, X_S and X_{BH} in effluents from different outlets

According to Fig.2, the concentration of X_S and S_S in effluents from Tank 4 in the single-feeding is higher than the step-feeding. It is clear that there exist large differences on X_S between two methods: the concentration of X_S is 10.98mg/ L in the step-feeding which is much higher than 5.98mg/L in the single-feeding. However, the difference between the concentrations of S_S in two different processes is rather smaller, 1.36 and 2.64mg/L respectively, since S_S can be easily used by X_{BH}. As single-feed process can remove organics more effectively, and consequentially more substrates are converted to X_{BH}, the total concentration of X_{BH} （835.73 mgCOD/L） in single-feeding is higher than that （825.02mgCOD/L）in step-feeding. This is because X_S has to hydrolyze into S_S before being used by aerobic growth of X_{BH} [9].

In WWTPs, because activated sludge has strong capability of adsorption for organics, organics adsorbed in return sludge will become the carbon source of denitrification and dephosphorization. Since single-feeding would consume more organics and step-feeding can save organics, thus the latter can be used for denitrification and dephosphorization in WWTPs with inadequate carbon source.

Changes of S_{NH} and X_{BA}. The result of simulation indicates that the concentration of S_{NH} from the outlet of Tank 4 is 2.61 (step-feeding) and 3.03mg/L (single-feeding) respectively. In comparison, although there has little difference, step-feeding is better than single-feeding. From Fig. 3, it can be seen that the concentration of X_{BA} under step-feed process is higher than the other. After the first round of simulation, the increase of biomass under single-feeding is 3.366mgCOD/L with an increasing rate of 7.57%, while the increase of biomass in step-feeding is 3.540mgCOD/L with an increasing rate of 7. 97%.

The concentrations of sludge in the tanks with step-feed process distribute gradedly with a high beginning concentration and a fast reaction rate. However, with the adoption of equal-proportional step-feed process in this example, as the concentration of sludge in the tanks goes lower, the removal rate of S_{NH} decreases and the concentration of S_{NH} from the outlets increases gradually as shown in Fig. 3. In step-feeding, some of the sewage does not need to go through all the tanks which comparatively increase the retention time of sludge in the tanks. In this example, by single-feeding, the HRT in every tank is 0.056d on average, totaling 0.224d, while by step-feeding, the HRT in different tanks is 0.095, 0.077, 0.065 and 0.056d respectively, totaling 0.293d. Due to the same way of processing sludge in both the two methods, by step-feeding, the activated sludge can stay 0.07d longer in the tanks.

When the concentration of organics in the aerobic tanks is too high, the aerobic degradation of X_{BH} would constrain the aerobic nitrification of X_{BA}. But the design of Model ASM1 does not take the effect of this competitive inhibition into account. Therefore, in WWTPs, when the concentration of organics in the tanks is too high with single-feed process, nitrification would be inhibited and the concentration of S_{NH} from outlets is ever higher than that simulated by Model ASM1.

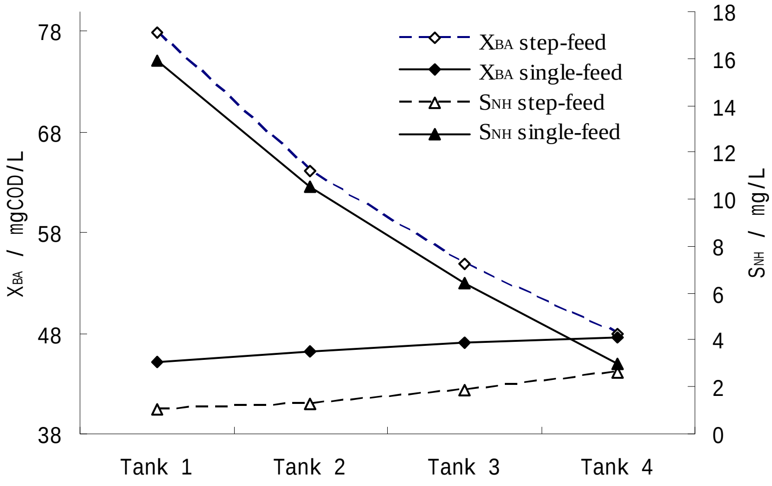

Fig. 3 Changes of S_{NH} and X_{BA} in effluents from different outlets

The Respiratory Rate of Nitrification

The amount of X_{BA} in the activated sludge can be shown directly through the nitrate respiratory rate. A higher respiratory rate indicts that the concentration of X_{BA} in the mixed liquid would be higher. In the research, we chose five different WWTPs to determine the respiratory capability of the mixed liquid and one of them would be in use of the step-feed process. Mixed liquid from the outlets of aerobic tanks was collected to measure the respiratory rate of nitrification. Then, the OUR and specific nitrification rates (SNR) were obtained in Table 3.

Table 3 The respiratory rate of nitrification in WWTPs mixed liquid

No.		Process	MLVSS [mg/L]	OUR [$mgO_2/(L\cdot d)$]	SNR [$mgO_2/(g\ MLVSS\cdot d)$]
No.1	A/O	four inlets step-feeding	2464	695	283
No.2	A/O	single-feeding	1962	248	127
No.3	A/A/O	single-feeding	3484	534	153
No.4	A/A/O	single-feeding	3563	341	111
No.5	A/A/O	single-feeding	1732	273	172

The result shows that by using step-feed process, we can get the highest OUR and SNR. OUR and SNR are 695 $mgO_2/(L\cdot d)$ and 283 $mgO_2/(L\cdot d)$ respectively and are 1.96 and 2.14 times respectively compared with the average values of the other four WWTPs. The result shows the X_{BA} concentration in activated sludge with step-feeding is higher than single-feeding.

Conclusions

In the activated sludge process, the step-feed process is suitable for the removal of S_{NH}, and good for the growth of X_{BA}. When the system using step-feeding goes stabilized, a higher concentration of X_{BA} can be obtained. The respiratory rate of nitrification of mixed liquid from the WWTP by using step-feeding is much higher than that by using single-feeding, in which the nitrate respiratory rate can reach 695 $mgO_2/(L\cdot d)$, 1.96 times higher than the average value of the other four sewage treatment plants.

Step-feed process is good for the removal of S_{NH}, while the single-feed process is suitable for the removal or organics. Therefore, a WWTP whose process is dominated by the removal of organics should adopt single-feed process, while for other WWTP whose process is dominated by the removal of S_{NH}, it is better to adopt step-feed process. For the plants which do not have enough carbon sources in their influent, they can consider to use step-feed process to save carbon sources.

Acknowledgements

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Nomenclature

C_{ki}	Concentration of component in the *i* tank
$C_{k,r}$	Concentration of component in the return sludge
$C_{k,inlet}$	Concentration of component in the influent
$C_{k,outi-i}$	Concentration of component in the effluent in the ***i***-1 tank
Q_{in-i}	Step-feed flow rate of the *i* tank
Q_r	Flow rate of return sludge
V_i	Volume of the *i* tank
Q_{outi}	Flow rate of the ***i*** tank

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