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Effects of Hourly Load Variation on Treatment Characteristics in Anaerobic-Aerobic Activated Sludge Process

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Abstract—The effect of hourly load change on the treatment characteristics in an anaerobic-aerobic activated sludge process was compared for two types of variation. When the variation of wastewater concentration or flow rate was applied to the treatment unit according to normal distribution function like effluent pattern in actual life, the treatment system gave relatively stable and successful removal of nitrogen and phosphorus compounds. When the mass flow rate of nitrogen applied to the treatment unit was equal, the performance of the present process was almost same regardless of load variation mode. The simulation of treatment behavior was carried out successfully by using the kinetic equations for sludge floc and the reactor models which considered the treatment unit as a completely mixed tank.

Key words: Anaerobic-Aerobic Operation, Gray Water, Activated Sludge Process, Nitrogen Removal, Phosphorus Removal, Load Variation

INTRODUCTION

Nitrogen and phosphorus in a watercourse originate from many sources such as artificial fertilizers in farmland, many manufacturing plants and, in particular, from domestic sewage wastewater. Major problems which arise from sewage effluent discharged without treatment are nutrient enrichment, i.e., eutrophication. By far, the most economical and successful technique for nitrogen removal is to use the reactions occurring in the biological nitrogen cycle. In this case, ammonification and nitrification proceed by aerobic operation, whereas denitrification proceeds by anaerobic operation [Rittmann and Langeland, 1985]. Further, the microbes responsible for each step are different. Therefore, the conventional biological treatment systems for nitrogen removal have been equipped with two or three tanks to satisfy the quite different requirements of nitrification and denitrification concerning the dissolved oxygen concentration [Lee et al., 1998; Barth and Stensel, 1981]. However, such a system becomes necessarily large, and in addition, any organic carbon compounds must be added to anaerobic tank as a hydrogen donor to promote the denitrification [Tom et al., 1992; Dahab and Lee, 1988].

Fuhs and Chen [1975] noted the relation between the release and uptake of phosphorus. They observed that a pure culture of *Acinetobactor*, batch fed with acetate and subjected to an anaerobic/aerobic cycle, released phosphorus in the anaerobic phase, and removed the released phosphorus by rapid uptake in the aerobic phase. When the acetate feed stopped, phosphorus release in the anaerobic phase was not experienced, and in the aerobic phase a very slow release (instead of uptake) was observed. They also recognized the production of substances such as methanol, acetate, succinate as the principal function of the anaerobic zone in the phosphorus removing system. Many workers supported the view that the function of the anaerobic period is to produce fermentation products which are utilizable by the *Acinetobactor* [Lee et al., 1999; Brodish, 1985; Buchan, 1983; Deinerna et al., 1975]. Some workers proposed as the primary function of the anaerobic zone, the “stressing” of the organism to stimulate the phosphorus release and the subsequent phosphorus uptake in the following aerobic zone [Nicholls and Osborne, 1979].

Recently, the single sludge process in which the removal of nitrogen and phosphorus together with BOD proceeds simultaneously has become of interest from the viewpoints of cost and simplicity of operation [Hashimoto, 1989; Argaman and Brenner, 1986; Barnard, 1973]. The anaerobic-aerobic activated sludge process was investigated as a small-scale single sludge treatment unit of gray water [Lee et al., 1997]. The treatment system proposed gave a relatively stable performance against stepwise change of the influent flow rate. However, another important problem in the treatment of gray water is the change of load caused by concentration fluctuation. The concentration of pollutants changes hourly, especially in the morning and evening.

In this study, therefore, the transient behavior of the system was examined when the wastewater concentration or flow rate was changed according to normal distribution function. This mode of variation is more close to actual effluent compared to the stepwise change [Lee et al., 1997]. Also, the treatment performance against the flow rate variation was compared with that for concentration variation while keeping the load to the process during one day equal. The simulation of the process was carried out by a kinetic model of the sludge floc which considered the oxygen profile inside the floc and the reactor model which considered the treatment unit as a completely mixed tank.

EXPERIMENTAL

The experimental apparatus used was quite similar to Banard’s system [Barnard, 1973] as shown in Fig. 1. A baffle plate was placed

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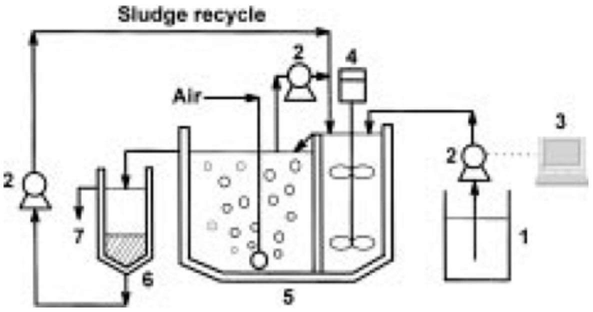

Fig. 1. Schematic of experimental apparatus.

1. Feed tank	5. Reactor
2. Pump	6. Settler
3. Computer	7. Effluent
4. Stirrer	

Table 1. Composition of synthetic wastewater

Components	Concentration (g/m^3)
Glucose	200
Polypepton	40
$(NH_4)_2SO_4$	21.7
KH_2PO_4	6.6
$NaHCO_3$	37.5
$MgSO_4 \cdot 7H_2O$	56.3
$CaCl_2 \cdot 2H_2O$	37.5
NaCl	37.5

Org-N : NH_4^+-N=5.4 : 4.6
BOD=150 g/m^3
T-N=10 g/m^3
T-P=1.5 g/m^3
BOD : N : P=75 : 5 : 1

in the tank having total volume of 10 dm^3, so as to give equal volume for both anaerobic and aerobic regions. The artificial wastewater, shown in Table 1, contained glucose as a main carbon source and some inorganic salts as nutrients. It was introduced to anaerobic region first to promote the denitrification by utilizing the organic carbon compound in the wastewater, then to the aerobic region where ammonification and nitrification proceeded under aeration. The mixed liquor was recycled from aerobic to anaerobic region and the effluent was withdrawn from aerobic region. The influent flow rate or concentration was changed by computer-controlled pumps according to the effluent pattern of actual gray water in such a way that two peaks of load appeared in the morning and evening and the load variation followed the normal distribution function. The experimental data was taken at ten days after the start of hourly load change when the same change of concentration during one day was repeated for each component. Load variation tests were operated for three weeks each. In this study, the peak coefficient (P) was defined as the ratio of a maximum to an average flow rate and the recycle ratio (R) was defined as recycle flow rate versus average influent flow rate. The performance of this unit was investigated under the standard operating conditions, such as average hydraulic residence time of 24 h, recycle ratio of 1, aerobic/anaerobic volume ratio of 1, temperature of 25 °C, MLSS of 3,000 to 3,600 mg/L and sludge age of 30 d. The average concentration per day of wastewater was as follows: COD_{Mn}=125 mg/L, T-N (total nitrogen)=10 mg/L, and PO_4^--P=1.2 mg/L. NH_4^+-N was determined by the indophenol blue method, T-N by Ultraviolet absorption method, and NO_3^--N and PO_4^{3-}-P by ion chromatography (DIONEX DX-120).

RESULTS AND DISCUSSION

1. Characteristics of Treatment Unit Against the Variation of Influent Flow Rate

Gray water has a remarkable feature that the flow rate and concentration vary during a day according to our mode of living. The response of an anaerobic-aerobic activated sludge process against the variation of influent flow rate during a day was first measured while keeping the concentration constant. The treatment characteristics at peak coefficient (P) of 3 and recycle ratio (R) of 1, are shown in Fig. 2. The time course of the influent flow rate was set by normal distribution function as shown in the upper part of the figure. The present system gave a relatively stable performance against hourly change of the flow rate and showed a satisfactory removal of nitrogen and phosphorus, although the concentration of each component changed slightly in both regions.

2. Characteristics of Treatment Unit Against the Variation of Influent Concentration

The response of anaerobic-aerobic activated sludge process against the variation of concentration was investigated under constant influent flow rate. Influent was made to stop when the concentration was zero. Fig. 3 shows the results at peak coefficient of 3 and recycle ratio of 1. The transient behavior of each component

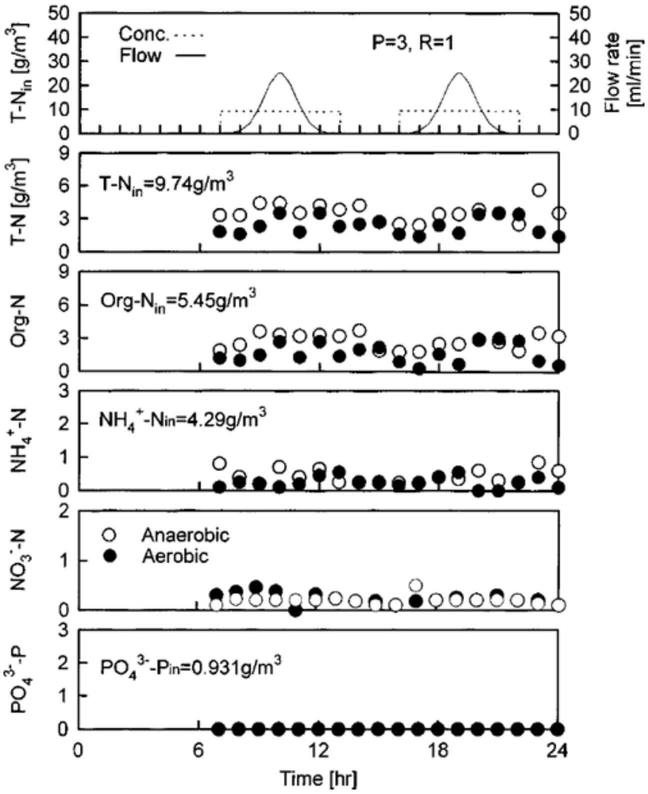

Fig. 2. Time course of treatment performance on flow rate variation at peak coefficient of 3.0.

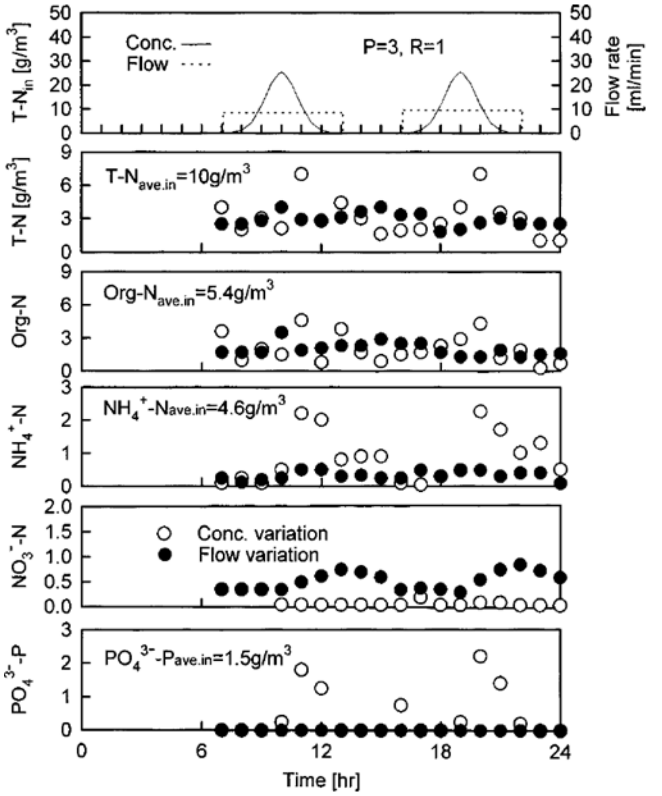

Fig. 3. Time course of treatment performance on concentration variation at peak coefficient of 3.0.

was similar to that observed in the variation of flow rate shown in Fig. 2. Although the concentrations in the aerobic region showed a stable behavior, those in the anaerobic region increased substantially when the influent concentration rose at the peak points. This is a little different from the result in flow rate change in which case the concentration changes in the anaerobic region were almost similar to those in the aerobic region. This is because, in the case of flow rate variation, the effect of flow rate increase may be relaxed by direct overflow from anaerobic to aerobic region. However, in the case of concentration variation, the anaerobic region receives the influence of concentration peak strongly since the flow rate is kept constant.

3. Effect of Concentration Peak Coefficient

The effect of peak coefficient on the extent of removal was investigated for concentration variation. As shown in Fig. 4, the removal of T-N and phosphorus scarcely changed with peak coefficient. It was considered that the influence of concentration peak was moderated during the flow from anaerobic to aerobic region. The high concentration components in the influent wastewater are rapidly dispersed throughout the first-stage reactor, anaerobic region, then sent into the second-stage reactor, aerobic region. Since each reactor is a completely mixed reactor, the dilution effects contribute effectively to lower the concentration. Therefore, the treatment system in this study can produce an effluent of relatively uniform quality in spite of large fluctuations in influent load.

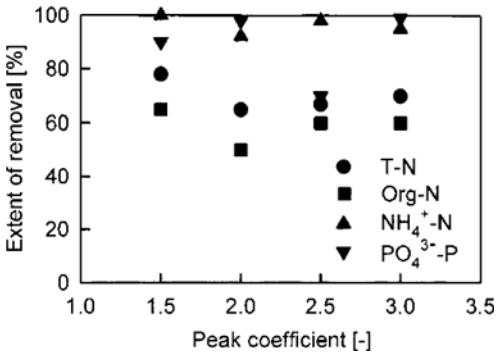

Fig. 4. Effect of peak coefficient on the extent of removal.

4. Comparison of Treatment Performance Against Two Types of Load Variation

Under the condition that the load applied to the treatment unit during one day is equal, the change of T-N concentration at the exit, aerobic region was compared for flow rate variation and concentration variation. Fig. 5 plots the change of T-N concentration in the effluent at peak coefficient of 3 and recycle ratio of 1. As shown in the figure, T-N concentration did not show a great difference in both cases, although in concentration variation it was a little higher than that in flow rate variation at the vicinity of peaks.

5. Modeling of Treatment Process

Fig. 6 draws the basic flow of wastewater and mixed liquor in the present treatment unit. Each treatment tank, aerobic and anaerobic, was considered as a completely mixed tank reactor. The unsteady-state mass balance equations for i-component in both regions are written as follows, respectively:

Anaerobic region: $dC_{i2}/dt=(C_{i1}-C_{i2})(Q_o+Q_r)/V_{AN}+r_ia_{AN}$

Aerobic region: $dC_{i3}/dt=(C_{i2}-C_{i3})(Q_o+Q_r)/V_{AE}+r_ia_{AE}$

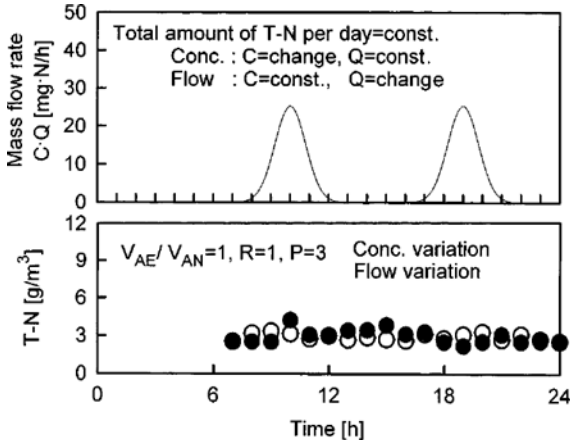

Fig. 5. Comparison of effluent nitrogen concentration in concentration variation and flow rate variation.

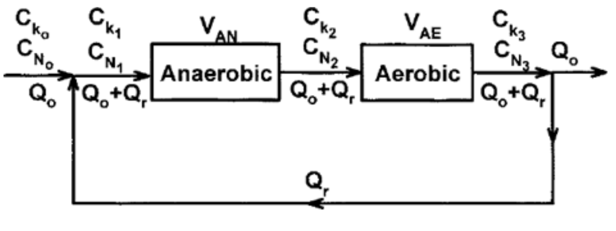

Fig. 6. Flow of anaerobic-aerobic activated sludge system.

Table 2. Kinetic constants used in simulation

Kinetic constants	Values (g/m^{3}h)
k_A	0.898
k_N	28.75

where, $C_{i1}=(C_{io}\cdot Q_o+C_{i3}\cdot Q_r)/(Q_o+Q_r)$.

The reaction kinetics of nitrogen compounds was derived by considering the simultaneous nitrification and denitrification in the single sludge. The flux equations of the sludge floc were found to be classified into four cases according to the bulk concentrations of each nitrogen component and dissolved oxygen [Hano et al., 1992a]. The rate constants in these kinetic equations were evaluated by measuring the dependences of reaction rates of two nitrogen components on the dissolved oxygen concentration and sludge floc size. The details of sludge floc modelling were described in our previous paper [Hano et al., 1992b]. The kinetic constants used in simulation are listed in Table 2.

6. Parameter Evaluation of Anaerobic-Aerobic Activated Sludge Process

By using the above models, the transient behavior of anaerobic-aerobic activated sludge process was simulated. Fig. 7 shows the results of simulation for T-N concentration at aerobic and anaerobic regions in case of concentration variation. The calculated results for T-N concentration at the exit under recycle ratio of 1 are indicated by a solid and dotted line for peak coefficient of 2 and 3, respectively. The upper part of Fig. 7 shows the variation of total nitrogen added to the system which was set by normal distribution function according to actual effluent pattern. The calculated results agreed successfully with the experimental results, except at the range of low concentration. Fig. 8 shows the extent of T-N removal at various peak coefficients in the variation of concentration and flow rate. The extent of removal shown in Fig. 8 is the average T-N removal per day and is almost same in both cases. This finding may be explained as the load applied to the microbes being equal regardless of load type, because the load applied to the process during one day is equal. The extent of removal slightly decreased with increasing peak coefficient.

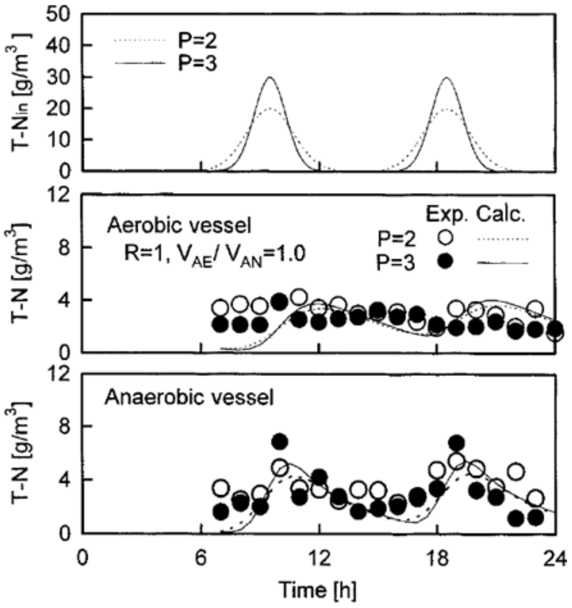

Fig. 7. Comparison of calculated and obtained concentration of total nitrogen.

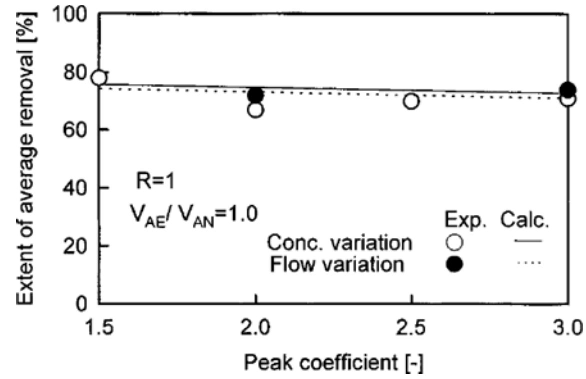

Fig. 8. Comparison of calculated and observed extent of total nitrogen removal.

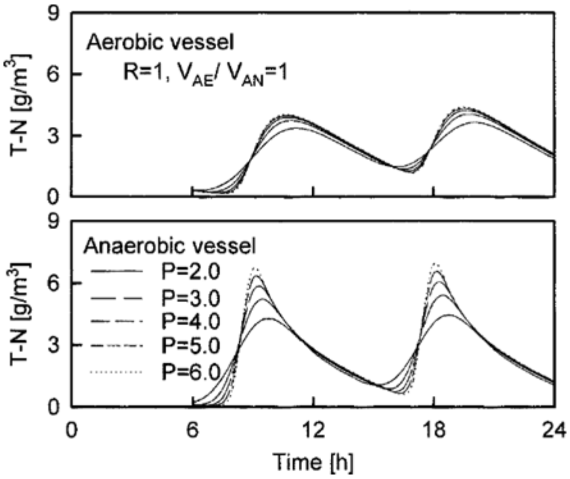

Fig. 9. Effect of peak coefficient on total nitrogen concentration at each region.

The effects of operating parameters were examined by calculation based on simulation model. The principal operating parameters in the present system are recycle ratio, peak coefficient and volume fraction of aerobic region. Fig. 9 shows the calculated result for the effect of peak coefficient on the change of T-N concentration at the exit. T-N concentration increased with increasing peak coefficient. However, the effect of peak coefficient in the aerobic region was smaller than that in the anaerobic region.

Fig. 10 shows the calculated result for the effect of recycle ratio on T-N removal. The extent of removal gradually increased with raising the recycle ratio, but the influence of recycle ratio was not large. The rise of recycle ratio results in an increase of the mixing degree, and the concentration difference between anaerobic and aerobic region becomes insignificant. However, at high recycle ratio, the lack of organic carbon as a hydrogen donor might result in the drop of nitrogen removal in a carbon-limited system [Barnard, 1973].

In the present process, how to establish aerobic and anaerobic conditions appropriately in the system is the most essential. From

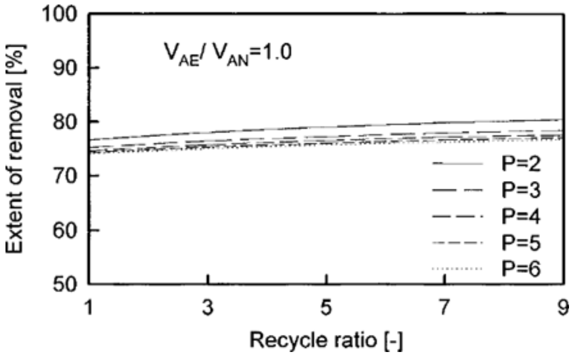

Fig. 10. Effect of recycle ratio on the extent of total nitrogen removal.

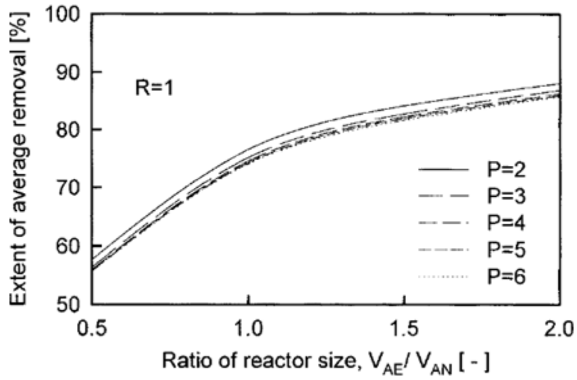

Fig. 11. Effect of aerobic tank size on the extent of total nitrogen removal.

Fig. 11, the extent T-N removal at various volume ratios of aerobic versus anaerobic region can be predicted. The drop of the removal extent at low volume ratio was caused by the depression of nitrification. High extent of removal was obtained with increasing the fraction of aerobic region. This feature can be explained by the fact that the rate-limiting step in the overall step is usually the nitrification step, although the optimum size depends on the relative activities of nitrification and denitrification steps. Consequently, the present model could predict the transient behavior of anaerobic-aerobic activated sludge process satisfactorily.

CONCLUSIONS

The transient behaviors of the anaerobic-aerobic activated sludge process against hourly variations of flow rate and concentration were examined by changing the load according to actual effluent pattern. The present treatment system gave a relatively stable performance against load change and showed a satisfactory removal of nitrogen and phosphorus compounds. It was considered that the present activated sludge process is well suited for the treatment of wastewater subject to load fluctuation. From comparison of the treatment performance against two types of load variation, the concentration variation and the flow rate variation, it was found that the treatment unit gave the same effluent quality regardless of load variation type. The simulation of treatment performance was carried out successfully by using the kinetic equations and the reactor models which considered the treatment units as two complete mixing tanks.

The transient behavior of an anaerobic-aerobic activated sludge process could be predicted by the present model successfully. The recycle ratio of mixed liquor from aerobic to anaerobic region, peak coefficient, and the volume ratio of both regions primarily controlled the extent of nitrogen removal.

NOMENCLATURE

a_{AE} : specific surface area of floc in aerobic region [m^2/m^3]
a_{AN} : specific surface area of floc in anaerobic region [m^2/m^3]
C_i : concentration of i-component [g/m^3]
P : peak coefficient [-]
k_A : zero-order reaction rate constant of nitrification [$g/m^3 \cdot h^1$]
k_N : zero-order reaction rate constant of denitrification [$g/m^3 \cdot h^1$]
Q_o : volumetric flow rate of influent [m^3/h^1]
Q_r : volumetric flow rate of recycle flow [m^3/h^1]
R : recycle ratio of mixed liquor [-]
r_i : reaction rate of i-component [$g/m^3 \cdot h^1$]
t : time [h]
V_{AE} : volume of aerobic region [m^3]
V_{AN} : volume of anaerobic region [m^3]

Subscripts

1 : input in anaerobic region
2 : input in aerobic region
3 : output in aerobic region

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