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EFFICIENCY OF AERATION METHODS FOR NITROGEN TREATMENT IN A WASTEWATER TREATMENT PLANT

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Abstract: This paper presents the result of comparing two methods of total nitrogen reduction in the same wastewater treatment plant: 1) the use of one biological tank with a discrete aeration operation (ON / OFF); 2) the use of two biological tanks with continuous aeration operation for the only second tank (aerobic), the first one works like an anoxic tank. In both cases, the dynamic simulation and optimization are performed with measured data, and energy consumption for aeration operation to reduce the total nitrogen in the wastewater and other concentrations are considered to satisfy the discharge regulations. The comparison of these two methods is presented after optimization by the best operating condition. The result shows that the economic efficiency is not much different in the two methods, but in both of them, the energy consumption after optimization reduces by about 70% compared to the real operating policy of the wastewater treatment plant.

Keywords: wastewater treatment plant; dynamic optimization; energy consumption; nitrification and denitrification; nitrogen treatment.

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INTRODUCTION

For urban wastewater, in addition to treating the main pollutants such as BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), and TSS (Total Suspended Solids); TN (Total Nitrogen) is a substance easily exceeding the discharge regulations that wastewater treatment plants (WWTPs) are dealing with. For nitrogen reduction in wastewater, two steps can be carried out: nitrification and denitrification. Normally, nitrification is implemented in an aerobic tank, but denitrification can be carried out in two ways (two cases): (1) using two tanks, an anoxic tank for denitrification, and another one (aerobic tank) for nitrification, therefore, water containing several nitrates in the aerobic tank must be recycled to the anoxic tank for denitrification, and (2) using only one tank, aeration operation for nitrification, stop aeration operation for denitrification.

Most previous WWTPs used case 1 to reduce TN in wastewater. However, case 2 has been quite popular in recent years: Le *et al.* (2015) studied the development of sequencing batch reactor performance for nitrogen wastewater treatment, but the authors only mentioned the processing efficiency of the method without mentioning the maximum performance when the system has been optimized. Smyk and Ignatowicz (2018) presented the efficiency of nitrogen removal from wastewater using Brenntaplus VP1 as an external carbon source, but not an intermittent aeration operation adjustment for the SBR that is important for the treatment of nitrogen in the wastewater. Fan and Xie (2011) performed optimization control of the SBR wastewater treatment process based on pattern recognition but did not compare performance with other optimization methods. Typically, a WWTP is studied by Chachuat (2001). This WWTP supplies air-ON and air-OFF alternately to perform two processes (i.e., nitrification and denitrification). Benois's study carried out the simulation and optimization process to find the alternate aeration operation that best suits the characteristics of the influent stream, the results showed that after optimizing, reducing the energy of the aeration operation system by 40%.

The question is posed for case 1 if the simulation and optimization method is carried out similarly to case 2, which case achieves higher economic efficiency? What are the advantages and disadvantages of the two cases in choosing the right treatment method? The purpose of this study is to answer these questions. The research results show the similarities between the two methods, but there are some differences when applied. However, it is impossible to compare the two treatment methods if the WWTP is not optimized. To optimize the WWTP, the first necessary step is the simulation. The simulation and optimization are rather complex tasks, especially the measurement process to adjust between the theoretical model and the actual operation of the WWTP. Currently, there are some typical WWTP simulation models such as ASM1, ASM2 developed by Henze *et al.* (1987) and Gujer *et al*. (1995), ASM3 developed by Gujer *et al*. (1999), ASM2d developed by Henze *et al*. (1999), BSM1 developed by Alex *et al.* (2008). They are applied depending on the characteristics of the wastewater. The simulation and optimization work has also been mentioned by some authors, such as Rainier Hreiz *et al.* (2015) studied optimal design and operation of activated sludge processes: state-of-the-art, this work mentioned operation of the WWTP, not about the wastewater treatment method; Drewnowski *et al*. (2018) presented computer simulation in predicting biochemical processes and energy balance at WWTPs, the purpose is to operate the WWTP, not to optimize. Issa (2019) presented the optimization of wastewater treatment plant design using dynamic process simulation for a WWTP in Iraq. This study is only based on the concentration of BOD and TSS, not all pollutants in wastewater; Muoio *et al.* (2019) presented optimization of a large industrial WWTP using a modeling approach, the objective of this work is only to find the optimum solid retention time of a WWTP, which minimizes operating costs, using a modeling approach, not to mention the aeration operation; Sina Borzooei *et al.* (2020) studied the energy optimization of a WWTP based on energy audit data, not measurement data; Nguyen et al. (2020) and Nguyen and Latifi (2020) presented simulation and optimization of a WWTP with measurement data based on traditional wastewater treatment. Hence, there are many different purposes, but mainly to reduce the cost of investment and operation of WWTP, not to compare the wastewater treatment method, especially about reduction of nitrogen in the WWTP. Our study differs from the above studies, we will compare the best method to apply for a WWTP to satisfy discharge regulations and economic efficiency based on the ASM1 model and the gPROMS platform's advanced process modeling language.

RESEARCH METHODOLOGY

Process description

The process is a real treatment plant which is designed for 15000 population equivalent. It consists of a only aeration tank $V = 2047\ m^3$ equipped with three turbines (mechanical surface aerators, $\mathcal{P} = 3 \times 30kW, k_L a = 4.5h^{-1}$ and mix the influent flow with biomass **(Fig. 1)** (Chachuat *et al*., 2005a; 2005b). The settler is a cylindrical tank$A^{set} = 855\ m^2$, $H^{set} = 2.8\ m$ from which the solids are either recirculated to the aeration tank$Q^r = 7600\ m^3 d^{-1}$, or extracted from the system $Q_w = 75\ m^3 d^{-1}$.

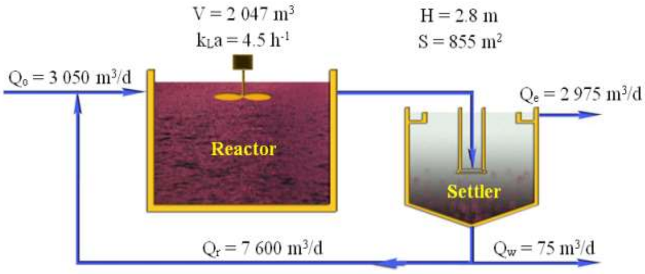

Fig. 1 Typical activated sludge treatment plant

The influent flow rate Q_o for two cases which is studied here are the same with the average influent flow rate $\overline{Q_o} = 3\,050\ m^3 d^{-1}$, average organic $\overline{COD}_{in} = 343\ g.m^{-3}$ and average nitrogen $\overline{TN}_{in} = 33\ g.m^{-3}$ (after primary treatment). The daily variations of dry weather conditions are based on measured data from the WWTP. It is accounted for by defining weighting functions for both influent flow rate and organic load variations, $\tau_Q(t)$ **(Fig. 2)**.

It consists of an aeration tank $V = 2047\ m^3$ equipped with three turbines (mechanical surface aerators, $\mathcal{P} = 3 \times 30kW$) which provide the oxygen $k_La = 4.5\ h^{-1}$ and mix the biomass with the effluent being treated. The settler is a cylindrical tank $A^{set} = 855\ m^2$, $H^{set} = 2.8\ m$ from which the solids are either recirculated to the aeration tank $Q^r = 7600\ m^3 d^{-1}$, or extracted from the system $Q_w = 75\ m^3 d^{-1}$. The aeration system is operated based on pre-determined air-ON / air-OFF periods (air-ON: $k_La = 4.5\ h^{-1}$; air-OFF: $k_La = 0$) and the applied strategy is identical from one day to another; it corresponds to 11 aeration cycles per day **(Fig. 3**) and a cumulated aeration time of about $12.75\ h.d^{-1}$.

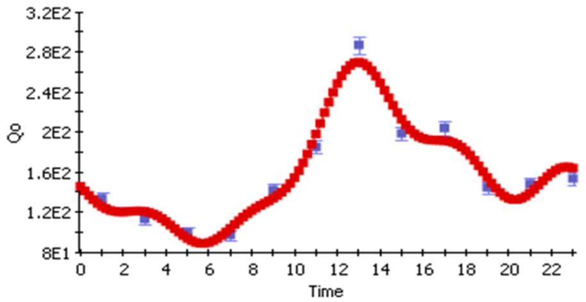

Fig. 2 Influent flow rate

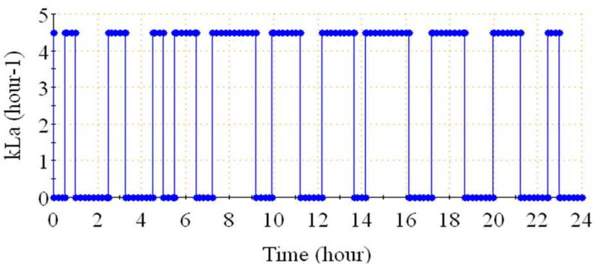

Fig. 3 Aeration profile in reality

Case study

The search is carried out in two cases:

__Case A__: use of one tank with the volume V = 2047 m³ **(Fig. 4)** and the aerator turbines, the discrete aeration condition: air-ON for nitrification, air-OFF for denitrification.

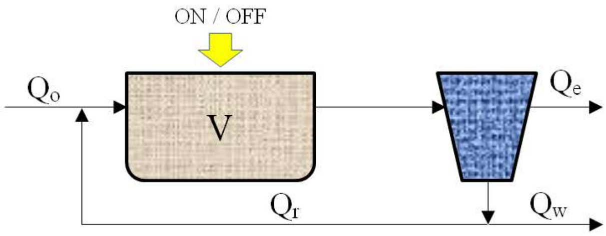

Fig. 4 Nitrogen reduction by ON/OFF mode

- Q_o, Q_r, Q_w, Q_e: flow rate of influent; external recycle; wastage and effluent, ($m^3.d^{-1}$).
- V: reactor volume, (m^3).
- k_La: oxygen transfer coefficient, (h^{-1}).

For this case, the aeration profile must be determined to minimize the aeration energy and meet the regulatory constraints.

__Case B__ : divide into two tanks: first tank does not need aeration ($k_La_1 = 0$) and functions as an anoxic tank by heterotrophic bacteria for denitrification, and the rest functions as an aerobic tank, so part of the water loaded with nitrates (Q_a) from the end of biological treatment (tank 2) is pumped and mixed with the inlet water at the head of treatment (tank 1); the second tank needs continuous aeration (k_La_2 = constant > 0) for nitrification by the aerobic condition **(Fig. 5).**

For this case, determine the volume of the second tank (V_2), the oxygen transfer coefficient in the 2nd tank (k_La_2) and the internal recycle (Q_a) to also minimize the aeration energy and satisfy regulatory constraints (COD_e, BOD_{5e}, TN_e, TSS_e).

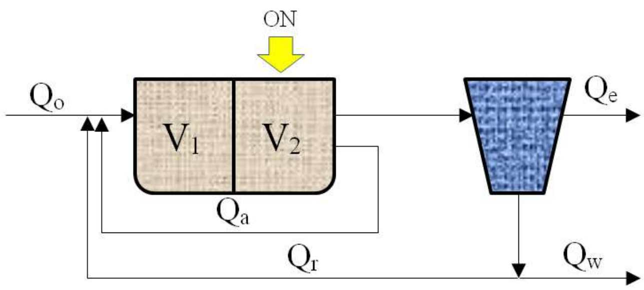

Fig. 5 Nitrogen reduction by aerobic and anoxic tanks

- V_1, V_2 : 1st and 2nd tank volume (m^3); where: $V_1 + V_2 = V = 2047\ m^3$.
- k_La_2: oxygen transfer coefficient in the 2nd tank, (h^{-1}).

- Q_a : internal recycle, (m^3d^{-1}).

Process modeling

The concentrations in this WWTP are based on the ASM1 model (*Activated Sludge Model n°1*) (Henze *et al*., 1987), but in this case, the model has been modified and identified to get the properties of the parameters by bringing this plant. Most of the parameters are the same cells that are given in the BSM1 model (*Benchmark Simulation Model n°1*) (Alex *et al*., 2008), except five identified parameters that have the following values (Y_H = 0.724; i_{XB} = 0.0674; μ_H = 5.1; κ_h = 2.23; f_{ns} = 0.00301).

In this case, the model presents 11 state variables that are presented in **Table 1.** The general equations for mass balancing in the reactor are as follows:

$$\frac{dx_i^{at}}{dt} = \frac{Q_r}{V}x_i^r + \frac{Q_{in}}{V}x_i^{in} - \frac{Q_{in}-Q_r}{V}x_i^{at} + \mathcal{R}_i \quad (1)$$

- x_i^{at}, x_i^r, x_i^{in} : concentrations of aeration tank, recycle and influent, g.m^{-3}.
- $\mathcal{R}_i$: reaction rate.
- V : reactor volumen (m^3).

A key point of the model is that the mass-balance equation for dissolved oxygen (DO) contains the additional term:

$$\mathcal{A}_0 = k_L a_i\left(S_O^{sat} - S_{O,i}^{at}\right) \quad (2)$$

$\mathcal{A}_0$ describes the oxygen transfer from the turbines during the air-ON periods.

Dissolved oxygen:

$$\frac{dS_O^{at}}{dt} = \frac{Q_r}{V}S_O^r + \frac{Q_{in}}{V}S_O^{in} - \frac{Q_{in}-Q_r}{V}S_O^{at} + \mathcal{R}_i + \mathcal{A}_0 \quad (3)$$

- S_O^{sat}: saturation concentration for oxygen, $(g.m^{-3})$.
- $S_{O,i}^{at}$: dissolved oxygen concentration in the i^{th} tank.

Table 1. List of variables

N°	Definition	Notation
1	Soluble inert organic matter	S_I
2	Readily biodegradable substrate	S_S
3	Particulate inerte organic matter	X_I
4	Slowly biodegradable substrate	X_S
5	Active heterotrophic biomass	$X_{B,H}$
6	Active autotrophic biomass	$X_{B,A}$
7	Nitrate and nitrite nitrogen	S_{NO}
8	$NH_4^+ + NH_3$ nitrogen	S_{NH}
9	Soluble biodegradable organic introgen	S_{ND}
10	Particulate biodegradable organic nitrogen	X_{ND}
11	Oxygen	S_O

- $k_L a_i$: oxygen transfer coefficient in the i^{th} tank, (h^{-1}).

This study uses the simplified model, so the concentrations in the clarifier are calculated as follows (Henze *et al.,* 1987):

$$S_i^e = S_i^{at} \quad (4)$$

$$X_i^e = f_{ns}.X_i^{at} \quad (5)$$

$$S_i^r = S_i^{at} \quad (6)$$

$$X_i^r = \vartheta.X_i^{at} \quad (7)$$

- S_i^e, X_i^e : soluble and particulate effluent concentrations, $(g.m^{-3})$.
- S_i^r, X_i^r : soluble and particulate recycle concentrations $(g.m^{-3})$.

The aeration energy AE (kWh.d^{-1}) is calculated from the $k_L a_i$ according to the following relation (Alex *et al*., 2001):

$$AE = \frac{S_O^{sat}}{T\cdot 1.8\cdot 1000}\int_{t_1}^{t_2}\sum_{i=1}^{n} V_i\cdot K_L a_i(t)\,dt \quad (8)$$

- T : period of observation, $T = t_f - t_0, (h)$.
- V_i : volume of the i^{th} tank (m³).
- n : number of tanks.

The concentrations used to characterize the effluent are calculated as follows:

$$COD_e = S_I^e + S_S^e + X_I^e + X_S^e + X_{B,H}^e + X_{B,A}^e \quad (9)$$

$$TSS_e = 0.75[X_I^e + X_S^e] + 0.9[X_{B,H}^e + X_{B,A}^e] \quad (10)$$

$$BOD5_e = 0.25[X_S^e + (1-f_p)(X_{B,H}^e + X_{B,A}^e) + S_S^e)] \quad (11)$$

$$TN_e(t) = S_{NO}^e + S_{NH}^e + S_{ND}^e + X_{ND}^e + i_{XP}X_I^e + i_{XB}(X_{B,H}^e + X_{B,A}^e) \quad (12)$$

- COD: Chemical Oxygen Demand.
- $BOD5$: 5-day Biochemical Oxygen Demand.
- TN: Total Nitrogen.
- TSS: Total Suspended Solid.

Effluent constraints (Alex *et al*., 2008): TN_{max}=10 mg.l^{-1}, COD_{max}=125 mg.l^{-1}, BOD_{5max}= 25 mg.l^{-1}; TSS_{max}=35 mg.l^{-1}.

Process optimization

The objective of this study is to determine the optimal aeration condition for case A (aeration profile) and case B (volume of second tank (V_2), aeration value (k_La_2) and internal recycling (Q_a)). Obviously, in both cases the concentrations on the effluent are satisfied.

Case A:

The aeration profile is described as a sequence of cycles, where each cycle is composed of an air-ON period followed by an air-OFF period. To characterize an aeration profile over a given time horizon $[t_o, t_f]$, one must specify first the number N_c of cycles. Two parameters must then be specified for each cycle in connection to the air-ON and air-OFF durations. In addition to N_c, the optimization parameters considered subsequently are: (i) the k^{th}-cycle duration l^k, and (ii) the k^{th}air-ON period duration a^k. From this description, the switching times t_b^k (from air-ON to air-OFF periods) and t_c^k (from air-OFF to air-ON periods) of the aeration system are defined in **Fig. 6**.

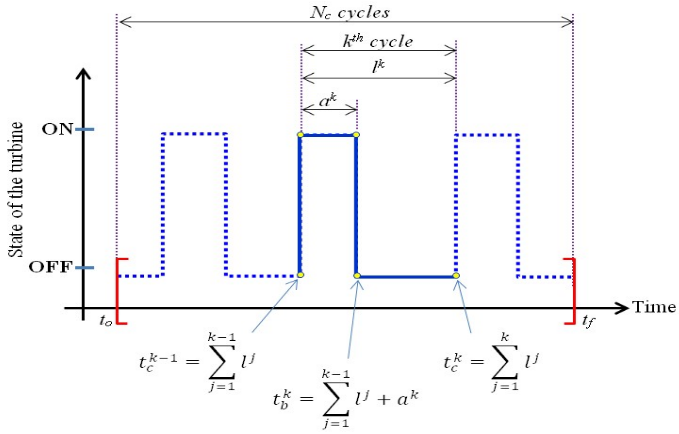

Fig. 6 Aeration profil ON/OFF

According to the aeration energy equation (8) and the aeration profile on **Fig. 6**. Determining the aeration policy that minimizes the energy consumption yields the following dynamic optimization problem:

$$\underset{N_c,a^1,l^1,\ldots,a^{N_c},l^{N_c}}{\text{Min}} \left\{ \frac{S_O^{sat}}{8\cdot 1000} \cdot \frac{\sum_{k=1}^{N_c} a^k}{\sum_{k=1}^{N_c} l^k} \cdot V \cdot k_L a \right\} \quad (13)$$

Subject to: $k_L a = 4.5$ if $t_c^{k-1} \le t < t_b^k$; $k_L a = 0$ if $t_b^k \le t < t_c^k$; $t_{min}^{ON} \le a^k < t_{max}^{ON}$; $t_{min}^{OFF} \le l^k - a^k < t_{max}^{OFF}$; $TSS_e \le TSS_{max}$; $TN_e \le TN_{max}$; $BOD_{5e} \le BOD_{5max}$; $COD_e \le COD_{max}$; $t_f = t_0 + \sum_{k=1}^{N_c} l_k$

The minimum time to stop (t_{min}^{OFF}) and operate the aerator (t_{min}^{ON}) is 15 minutes. The maximum time (t_{max}^{ON} *and* t_{max}^{OFF}) is 2 hours each time.

Case B:

According to the **Eq. (8)**, determining the aeration policy that minimizes the energy consumption yields the following dynamic optimization problem:

$$\underset{k_L a_2,Q_a,V_2}{\text{Min}} \left\{ \frac{S_O^{sat}}{(t_f - t_0)\cdot 1.8\cdot 1000} \cdot \int_{t_0}^{t_f} V_2 . k_L a_2(t)\,dt \right\} \quad (14)$$

Subject to: $TSS_e \le TSS_{max}$; $TN_e \le TN_{max}$; $BOD_{5e} \le BOD_{5max}$; $COD_e \le COD_{max}$; $0 \le k_L a_2 \le 15\ h^{-1}$; $Q_a \le 15\,250\ m^3.d^{-1}$; $V_2 = 2\,047 - V_1\ ,m^3$.

RESULTS

In the current case, the WWTP only functions as an experiment to satisfy the regulatory constraints, it is difficult to know how to rational operation to minimize energy consumption. We performed the simulation of the WWTP to determine the concentrations of the effluent and the value of the energy consumption of the aeration system. The results obtained for this current operation show that all concentrations on the effluent satisfy the constraints. Most of these concentrations are low except total nitrogen (TN) is quite high. This concentration of TN is presented on **Fig. 7**. As for the value of the aeration energy consumption is 652 $kWh.d^{-1}$.

In both cases that needs performance comparison, after optimization for both in order to satisfy the constraints and minimize the aeration energy, the results obtained as follows:

Case A: The number of cycles $N_c = 14$ (**Fig. 8**); the total operating time of aerator is 3.72 hours; the coefficient k_La in the case of air-ON is 4.5 h^{-1}. In this case, it is necessary to operate the aerator for a large tank ($V = 2047\ m^3$), with the operating time obtained above it is possible to determine the energy consumption of aeration by (8) is 190 $kWh.d^{-1}$. With this aeration policy, the majority of the concentrations on the effluent are quite low, except the concentration of TN reaches the bound (**Fig. 9**).

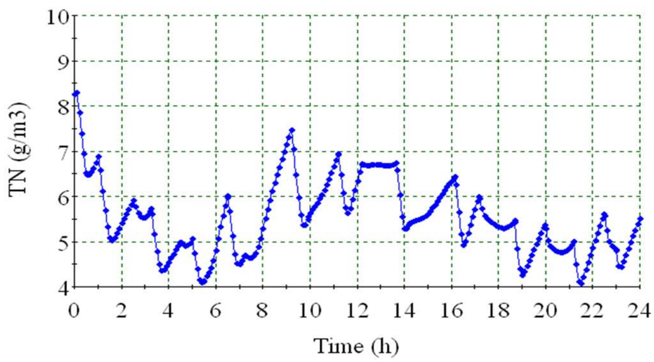

Fig. 7 Concentration of TN in reality

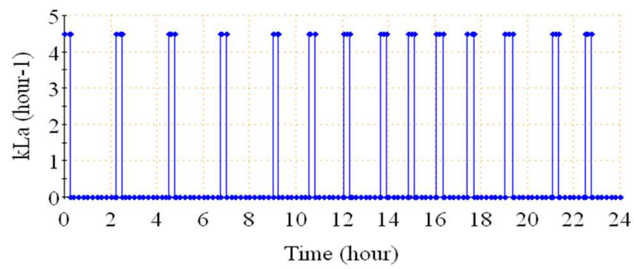

Fig. 8 Aeration profile for case A after optimization

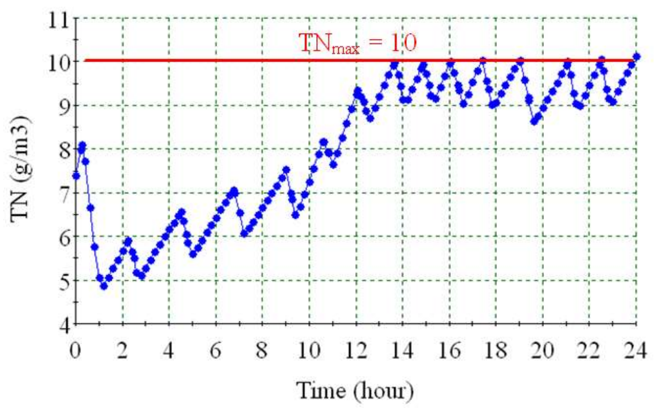

Fig. 9 Concentration of TN for case A after optimization

<u>**Case B**</u>: The volume of the anoxic tank is V_1 = 1864 m^3, of the aerobic tank is V_2 = 183 m^3 (**Fig. 10**). Internal flow rate is Q_a = 15250 m^3.d^{-1}. The oxygen coefficient in the second tank is k_La_2 = 7.66 h^{-1}.

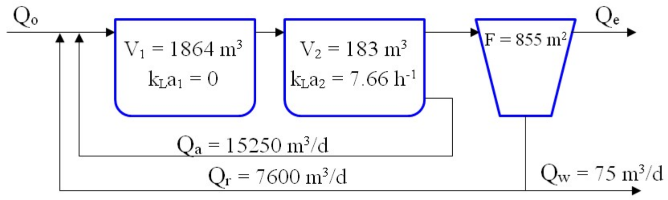

Fig. 10 The size of the WWTP for case B after optimization

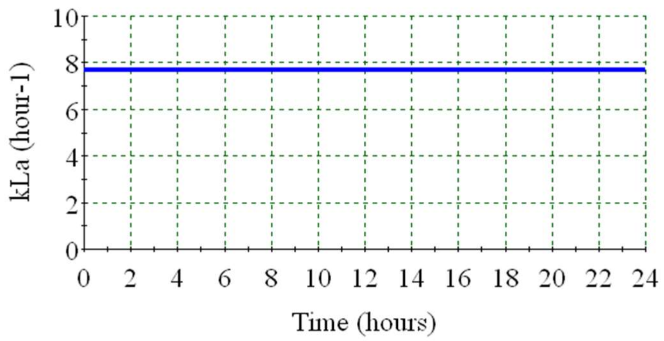

Fig. 11 Aeration profile for case B after optimization

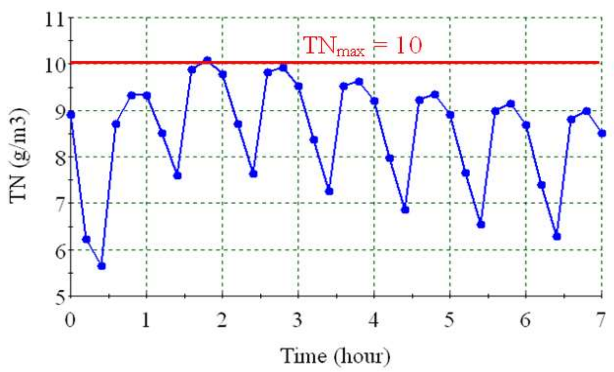

Fig. 12 Concentration of TN for case B after optimization

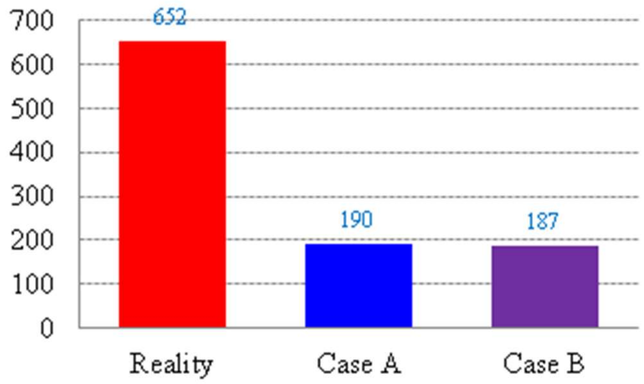

Fig. 13 Energy consumption for three cases (kWh.d^{-1})

In this case, it is necessary to operate the continuous aerator with the coefficient k_La = 7.66 h^{-1} for a second tank V_2 = 183 m^3 (**Fig. 11**). The same way, we can determine the energy consumption of aeration by (8) is 187 kWh.d^{-1}. According to this operation, most of the concentrations on the effluent are lower than constraints, except the concentration in TN reaches the constraint (**Fig. 12**). By bringing the operation into reality, the energy consumption of aeration for the three cases are presented in **Fig. 13**.

DISCUSSION

Fig. 13 shows that, the result of case A is consistent with the research results of Chachuat (2005a), So the result of case B is reliable to compare the two methods of wastewater treatment, from which there is a basis to choose the reasonable method suitable for each specific situation. Both methods show that after optimized the energy consumption to operate WWTP is greatly reduced (about 70% on energy consumption). The concentration of TN is very low by the constraint, it shows that this aeration policy wastes a lot of energy. As for the concentration of TN for case A and for case B shows that aeration policies are good agreements.

CONCLUSION

In both optimal cases (case A and B), the energy consumption of aeration operation is very economical compared to the case in the reality. Therefore, it is necessary to base on the concentration of the influent stream to operate the WWTP accordingly to reduce energy consumption. In order to do that, the optimization is necessary.

Energy consumption for aeration operation in the two methods is not much different, so to decide which method to mention the disadvantages of each:

<u>Case A</u>: it is necessary to operate the aeration policy in ON / OFF mode, this influences the longevity of the aerator motor, not good for operation, difficult to adjust to satisfy effluent standards.

Case B: the internal recycling pump must be used with the flow rate Q_a = 15 250 $m^3.d^{-1}$ but the operation is quite stable, easy to adjust if necessary.

This study is only studied for urban wastewater with a capacity of 15000 population-equivalent, it is necessary to have other studies to have better conclusions for other types of wastewater as well as other WWTP capacity.

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