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Automatic control strategy for step feed anoxic/aerobic biological nitrogen removal process

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Abstract: Control of sludge age and mixed liquid suspended solids concentration in the activated sludge process is critical for ensuring effective wastewater treatment. A nonlinear dynamic model for a step-feed activated sludge process was developed in this study. The system is based on the control of the sludge age and mixed liquor suspended solids in the aerator of last stage by adjusting the sludge recycle and wastage flow rates respectively. The simulation results showed that the sludge age remained nearly constant at a value of 16 d in the variation of the influent characteristics. The mixed liquor suspended solids in the aerator of last stage were also maintained to a desired value of 2500 g/m^3 by adjusting wastage flow rates.

Keywords: wastewater treatment; sludge age; control; modeling and simulation; step-feed process

Introduction

Step-feed anoxic/aerobic biological nitrogen removal process is characterized by the high nitrogen removal efficiency. The process has been found to offer relevant advantages for both new and existing plants. During the last decade, many works have been focused on this process (Gorgun, 1996; Larrea, 2001). In order to increase the safety and improve operating performance of step feed process, it is important to develop computer operational decision support system and intelligent control system. Therefore, intensive attention has been given to the control of the wastewater treatmentprocess and the control of the whole plant operation (Marsili-Libelli, 1989). The two most significant parameters used for this purpose are the rate of return sludge and the rate of the wastage activated sludge (WAS)(Pfister, 1998). The recycled activated sludge must provide sufficient concentration of biomass in the aerator to provide the required treatment efficiency despite of time-varying influent organic loading and flow rate, and the wasting of the sludge is necessary to keep either a given food to microorganism ratio or sludge age and to operate the settler under dynamic stability. The importance of sludge age as a control parameter is that the specific growth rate and thus the physiological state of the microorganisms in the system as well as the settling characteristics of the sludge can be controlled simultaneously (Takacs, 1991). Cakici and Bayrammoglu (Cakici, 1995) developed a new approach to control sludge age in the activated sludge process. But this approach cannot be applied in the step feed process because the mixed liquid suspended solids (MLSS) concentration is not uniform but changed along the influent flow distribution.

However, the optimum design and operation of the step-feed process is a difficult task because of the complexity of the reactor configuration and the influent flow distribution (Shigeo, 1996; Larrea, 2001; Peng, 2004). Volume ratios of anoxic and aerobic zone and wastewater fraction diverted from the inlet of the system are important parameters to be considered in the design of the step feed process. Wastewater characterization, especially influent C/N ratio, significantly affect the design. In this paper, an automatic control strategy for step-feed anoxic/aerobic biological nitrogen removal process is developed. The control strategies developed here are: (1) control of the MLSS in the last stage of the reactor to a desired value; (2) control of the sludge age to the setpoint.

1 Methodology

1.1 Mathematical model

Fig.1 is a schematic diagram of a step-feed anoxic/aerobic biological nitrogen removal process composed of a biological reactor volume V and a final settler of area A. The wastewater was pumped into the biological reactor steeply and then return sludge recycled to the first stage of the biological reactor. The rate of sludge growth in the biological reactor is assumed to follow Monod kinetics with microbial decay term. The dynamic model comprises the following equations:

Biological reactor:

$$\frac{\mathrm{d}X}{\mathrm{d}t} = \frac{Q}{V}rX_r - \frac{Q}{V}(1 + r)X + \frac{\mu_m SX}{K_s + S} - k_d X, \quad (1)$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \frac{Q}{V}S_i - \frac{Q}{V}S - \frac{1}{Y}\frac{u_m SX}{K_s + S}. \quad (2)$$

Settler:

Solid flux theory is used to calculate settler underflow sludge concentration X_r. By using the exponential approximation for the settling velocity (Vesilind, 1968), the following equation is derived for the settler underflow concentration:

$$X_r = \frac{nX_L^2}{nX_L - 1}. \quad (3)$$

Where X_L is the limiting underflow concentration, and is calculated iteratively as:

$$X_{L+1} = \frac{1}{n}\ln\left[\frac{U_0 A}{Q(r + w)}(nX_L - 1)\right], \quad (4)$$

$$U_0 = 6.466\exp(8.25 \times 10^{-4}\theta_c), \quad (5)$$

$$n = 10^{-3}[0.177 + 0.346\exp(-3.11 \times 10^{-3}\theta_c)]. \quad (6)$$

Sludge age can be expressed at different ways according to whether taking into account the biomass in the settler and sludge return line or not. Here, the following expression is used as suggested by Stall and Sherard (Stall, 1978).

$$\theta_c = \frac{VX}{QwX_r}. \quad (7)$$

1.2 Sludge age control strategy

Equation (7) can be rewritten as follows:

$$Qw = \frac{VX}{\theta_c}\frac{1}{X_r}. \quad (8)$$

As X_r and θ_c are kept constant by the control system, then the following equation can be obtained: according to the variable X_r:

$$\Delta(Qw) = -\frac{VX}{\theta_c}\frac{\Delta X_r}{X_r^2}. \quad (9)$$

According to the above differential equation, the Equation (9) can be rewritten as follows:

$$\Delta w(t) = -\frac{C}{Q(t)}\frac{\Delta X_r(t)}{X_r^2(t)} - w(t)\frac{\Delta Q(t)}{Q(t)}. \quad (10)$$

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Where C is a constant defined as $C = \frac{VX}{\theta_c}$ and $\Delta w(t) = w(t) - w(t-h)$. Equation (10) can be used to maintain constant sludge age by adjusting the waste ratio w.

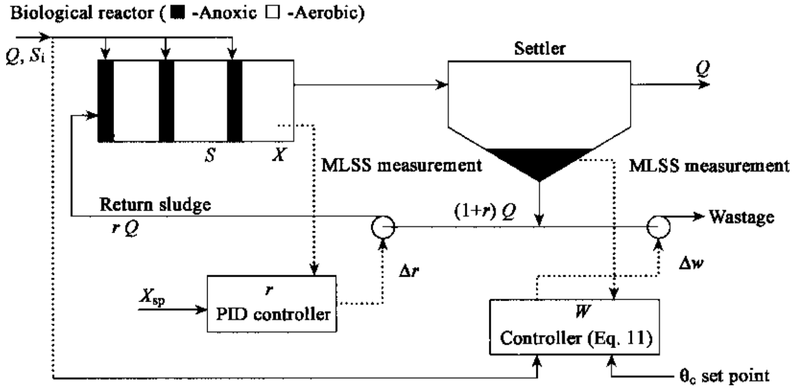

Fig. 1 Structure of the step-feed anoxic/aerobic biological nitrogen removal process and control strategy

1.3 PID controllers

Because of the operational reliability, functional simplicity, straightforward comprehension and strong robustness, the PID controllers still show great application in many industries including the wastewater treatment processes.

The basic PID controller model is described as follows:

$$u = K_p\left(e + \frac{1}{T_i}\int e\mathrm{d}(t) + T_d\frac{\mathrm{d}e}{\mathrm{d}t}\right), \qquad (11)$$

where: u is the control variable, e is the difference between controlled variable y and the setpoint r.

For computing conveniently, Equation (11) can be transformed from differential equation to difference equation, so make this approximation:

$$\int e\mathrm{d}t \approx \sum_{j=0}^{n} Te(j), \qquad (12)$$

$$\frac{\mathrm{d}e}{\mathrm{d}t} \approx \frac{e(n) - e(n-1)}{T}, \qquad (13)$$

substitute the Equation (12) and (13) into Equation (11)

$$u(n) = K_p\left\{e(n) + \frac{T}{T_i}\sum_{j=0}^{n} e(j) + \frac{T_d}{T}[e(n) - e(n-1)]\right\}. \qquad (14)$$

Where $u(n)$ is the control variable at the moment of n.

Equation (14) can be drawn as follows:

$$u(n-1) = K_p\left\{e(n-1) + \frac{T}{T_i}\sum_{j=0}^{n} e(j) + \frac{T_d}{T}[e(n-1) - e(n-2)]\right\}. \qquad (15)$$

Using Equation (14) minus Equation (15) the increment of $u(n)$ is obtained:

$$\Delta u(n) = K_p[e(n) - e(n-1)] + K_p\frac{T}{T_i}e(n) + K_p\frac{T_d}{T}[e(n) - 2e(n-1) + e(n-2)]. \qquad (16)$$

Namely:

$$\Delta u(n) = K_p\left(1 + \frac{h}{T_i} + \frac{T_d}{T}\right)e(n) - K_p\left(1 + 2\frac{T_d}{T}\right)e(n-1) + K_p\left(\frac{T_d}{T}\right)e(n-2). \qquad (17)$$

The discrete-time approximation of the PID controller is applied to manipulate the recycle sludge ratio to keep the MLSS level at the desired value(X_{sp}) as follows:

$$\Delta r(t) = K_p\frac{h}{T_i}X_{sp}(t) - K_p\left(1 + \frac{h}{T_i} + \frac{T_d}{h}\right)X(t) + K_p\left(1 + 2\frac{T_d}{h}\right)X(t-h) - K_p\left(\frac{T_d}{h}\right)X(t-2h), \qquad (18)$$

where $\Delta r(t) = r(t) - r(t-h)$, the sample interval h is taken as one minute.

In the application of PID control for MLSS and sludge age, temperature and pH of influent is 18℃ and 7.0 ± 0.2 respectively. The DO concentration of reactor is maintained at 2.0 mg/L. The structure of the PID controller is shown in Fig. 1 together with the WAS control.

2 Results and discussions

The step-feed activated sludge process was simulated using a nonlinear dynamic model in the section above. The system was subject to time-varying input representing the typical organic loading and the wastewater flow rate from a sewage system for a residential source with 15000 inhabitant equivalents, BOD loading rate 50 g/d, and wastewater flow rate 0.24 m^3/d(Fig. 2). The model was solved numerically using the explicit fourth-order Runge-Kutta method.

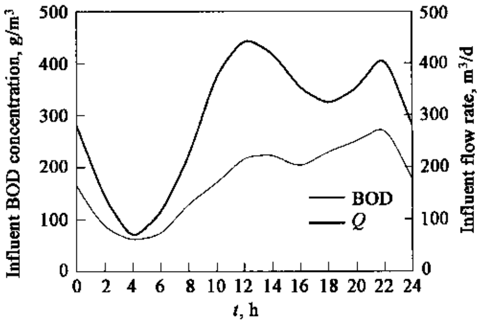

Fig. 2 Typical daily variations in flow compositions of domestic wastewater

Parameters used during the simulation studies are given in Table 1. A dynamic simulation was carried out for a sludge age of 16 d and MLSS in the last stage of 2500 g/m^3. The PID coefficients were tuned by serial log-lead method.

The resulting effluent BOD is shown in Fig. 3. The control strategy approached here is based upon the proposed sludge wastage policy to maintain the sludge age constant during plant operation. The relationship [Equation (11)] allows the θ_c to be constant at a value of 16 d during operation, as depicted in Fig. 4. It can be seen that the sludge age remains nearly constant in the variations of the influent characteristics. However, maintenance of the θ_c constant necessitates also to control MLSS in the last stage to a desired value. Fig. 5 indicates the performance of PID control for regulating the MLSS to the desired value in the last stage. The effect of the control strategy on waste ratio are depicted in Fig.6, where w increases significantly during the period when the loading decreases, whereas it decreases during the peak loading hours due to settler withdrawal.

Table 1 Model parameters and PID control coefficients

Model parameters			PID control coefficients		
Parameters	Value	Unit	Coefficients	Value	Unit
μ_m	0.0825	1/h	MLSS		g/m³
k_d	0.0025	1/h	K_p	0.55	—
K_s	60	g/m³	T_i	0.025	h
Y	0.5	-	T_d	0.025	h

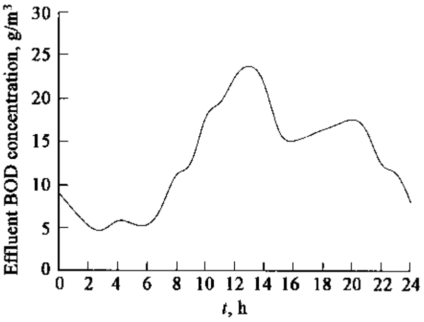

Fig.3 Variations of effluent BOD concentration

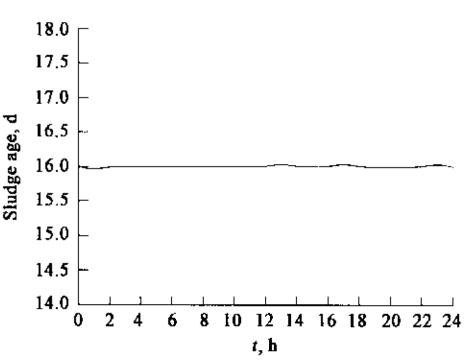

Fig.4 Control performance of sludge age to a constant set-point of 16 d

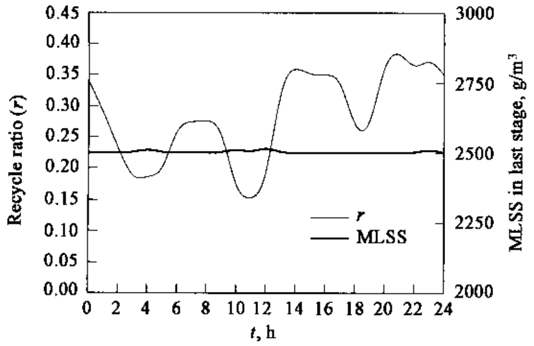

Fig.5 Performance of the MLSS PID control scheme to maintain a MLSS set-point of 2500 g/m³

3 Conclusions

Step-feed anoxic/aerobic activated sludge process shows great useful in biological nitrogen removal. The importance of sludge age as a control parameter is that the specific growth rate and thus the physiological state of the microorganisms in the system as well as the settling characteristics of the sludge can be controlled simultaneously. In this paper an automatic control strategy for step feed anoxic/aerobic biological nitrogen removal process is described. The control strategy mainly acted on : (1) MLSS control in the last stage of biological reactor; (2) control of the sludge age; (3) providing dynamic stability of the whole system. The maintenance of both sludge age and MLSS in the last of the reactor constant guarantees the dynamic stability of the step-feed activated sludge process. As a conclusion, a combination of these strategies may more effectively reduce effluent variability and provide better sludge quality during normal plant operation. Also, it is believed that the results obtained can be used to improve or develop an actual wastewater treatment plant.

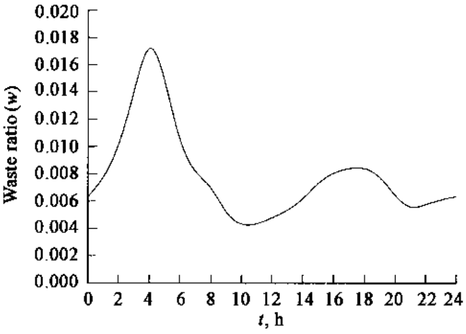

Fig.6 Variations of waste ratio w

Nomenclature: A—final settler area, m^2; h—sampling time, h; k_d—microorganism decay rate, 1/h; K_p—proportional gain; K_s—half-velocity constant, g/m^3; n—batch flux settling curve parameter, m^3/g; Q—influent flow, m^3/h; r—recycle flow ratio; S—organic material concentration, g/m^3; S_i—influent organic material concentration, g/m^3; t—time, h; T_d—derivative time constant, h; T_i—integral time constant, h; U_0—batch flux settling curve parameter, m/h; V—aerator volume, m^3; w—waste flow ratio; X—microorganism concentration, g/m^3; X_L—settler limiting underflow concentration, g/m^3; X_r-settler underflow concentration, g/m^3; X_{sp}—settler underflow concentration setpoint, g/m^3; Y—yield factor; μ_m—maximum specific growth rate, 1/h; θ_c—sludge age, d; BOD—biological oxygen demand, g/m^3, MLSS-mixed liquor suspended solids, g/m^3; PID—proportional-integral-derivative control; WAS—waste activated sludge.

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