A model to control intermittent aeration phases

A. Carucci*, M. De Mola, E. Rolle** and P. Smurra*****

* DIGITA, University of Cagliari, P.zza d'Armi, 09123 Cagliari, Italy (E-mail: *carucci@unica.it*)

** Department of Hydraulics, University of Rome "La Sapienza", Via Eudossiana 18, 00184 Rome, Italy (E-mail: *mademola@tiscalinet.it*; *enrico.rolle@uniroma1.it*)

*** Tecnica S.r.l., Via Cancelliera, 25, 00041 Albano Laziale, Rome, Italy (E-mail: *p.smurra@flashnet.it*)

Abstract Dealing with intermittent aeration as a useful practice to improve nitrogen removal efficiency of activated sludge plants, the possibility to plan optimal temporisation during daytime was investigated. A mathematical model (NIDEN) that allows us to manage different situations, with respect to influent load, environmental conditions and operating strategy, was then developed. The model represents a useful tool especially to plan the aeration cycles in small and medium sized plants, where high costs of automatic control through on-line instrumentation might not be justified. Once the input variables have been defined and the set-point values for tank nutrient concentration have been fixed, NIDEN gives an optimal phase temporisation, to obtain either the maximum energy saving or the best total nitrogen removal.

Keywords Activated sludge; intermittent aeration; model; nitrogen removal; on-line control; optimisation

Nomenclature

Q_i: influent flow (mc/d);
Q_{RIC}: return sludge flow (mc/d);
V: oxidation tank volume (mc);
V_{sed}: settling tank volume (mc);
DO: dissolved oxygen (mg/l);
T: temperature (°C);
$\bar{\mu}_A$: maximum specific autotrophic growth rate (d^{-1});
$\bar{\mu}_H$: maximum specific heterotrophic growth rate (d^{-1});
η_g: coefficient of heterotrophic growth in anoxic conditions;
Y_A: autotrophic growth yield (mgVSS/mgNH_4^+-N);
Y_H: heterotrophic growth yield (mgVSS/mgBOD_5);
K_{NH}: ammonia half-saturation constant for autotrophs (mgNH_4^+-N/l);
$K_{O,A}$: oxygen half-saturation constant for autotrophs (mgDO/l);
K_{NO}: nitrates half-saturation constant for heterotrophs (mgNO_3^--N/l);
$K_{O,H}$: oxygen half-saturation constant for heterotrophs (mgDO/l);
K_S: organic carbon half-saturation constant for heterotrophs (mgBOD_5/l);
f_H: heterotrophic biomass active fraction;
f_A: autotrophic biomass active fraction;
X_V: volatile solids concentration in the biological reactor (mgVSS/l);
i_{NXV}: nitrogen fraction in the biomass (mgN/mgVSS).

Introduction

In Italy, the endorsement in 1999 of the 91/271/EC Directive, has brought some innovations in the field of wastewater treatment with the result of stimulating new research regarding the more efficient strategies for total nitrogen removal (intended as the sum of ammonia, organic nitrogen, nitrite and nitrate fractions).

One of these is represented by *intermittent aeration*, consisting in the reduction of the

Water Science and Technology **Vol 46 No 4–5 pp 99–106** © IWA Publishing 2002

aeration time of the biological reactor by introducing periods without oxygen supply for the denitrification process. In such a way, a sequence of aerobic and anoxic phases occurs in the oxidation tank giving alternate time profiles of ammonia and nitrate. In the nitrification phase ammonium will be converted to nitrate and consequently the concentration of ammonium will decrease while the nitrate concentration will increase. In the denitrification phase, once oxygen is depleted, the nitrate concentration will decrease and the ammonium concentration will increase due to influent ammonia load.

Intermittent aeration, which can be easily introduced in pre-existing plants, gives the possibility to obtain a substantial energy saving (Carucci *et al.*, 1997), and a great operating flexibility (Zhao *et al.*, 1994a). In general, aerobic and anoxic phases are periodically alternated simply through the tuning of aeration system (i.e. fixed control of phase duration). In particular, the control strategy is addressed to complete nitrification in the aerobic phase (Thornberg *et al.*, 1993), and to reduce nitrate concentration during the anoxic phase in order to maximise total nitrogen removal efficiency.

The main purpose of this research was to study the possibility to plan optimal temporisation during daytime, thus developing a mathematical model (NIDEN) that allows us to manage different situations, with respect to influent load, environmental conditions and operating strategy. This model represents a useful tool especially to plan the aeration cycles in small and medium sized plants, where high costs of automatic control through on-line instrumentation might not be justified. Once input variables and fixed set-point values on tank nutrient concentration have been defined, NIDEN gives an optimal phase temporisation, to obtain either the maximum energy saving or the best total nitrogen removal.

In the following sections, the most important aspects of modelling, together with an explanation of the NIDEN algorithm, will be described.

Model description

Influent characterisation

In intermittent aeration, as a typical dynamic process, the characterisation of influent wastewater plays an important role, in relation to two different aspects (Carucci *et al.*, 1999). The first is represented by daily fluctuations, which determine hourly load peaks; the second is the subdivision of carbonaceous and nitrogenous matter into the various fractions, with regard to physical composition (soluble and particulate) and to the biodegradation behaviour (biodegradable and unbiodegradable). The knowledge of these fractions is important to determine oxygen demand and sludge production, as well as system biokinetics with respect to its nitrification and denitrification ability.

In order to obtain accurate and simple model equations, a distinction has been made between biodegradable and unbiodegradable fractions. As to the organic carbon substrate, only the biodegradable fraction (Cb), corresponding to BOD, was taken into account; this parameter includes both the soluble fraction (Cbs), related to influent BOD_5, and the particulate fraction (Cbp). Influent total nitrogen (Nt) is considered as TKN. The biodegradable fraction (Nb), that includes ammonia (Na) and an organic portion (Nob), has been considered completely as ammonia (easily degradable by biomass). The unbiodegradable fraction is composed of a soluble form (Nous) escaping with the effluent, and a particulate form (Noup) removed together with excess sludge.

Removal processes

In the NIDEN model, processes operating on BOD_5, NH_4^+-N and NO_3^--N, have been considered; nitrate is supposed to be the only oxidised nitrogen fraction. Nitrogen removal represents the most interesting aspect of modelling, therefore only its three fundamental processes (i.e. biomass growth, nitrification, denitrification) will be described.

Biomass growth gives a minor contribution, even if not negligible, to nitrogen removal. In fact, nitrogen is an essential component for new biomass synthesis.

As different experimental results have shown (Lukasse *et al.*, 1997), nitrification and denitrification can take place simultaneously. This feature is related to DO concentration: as a matter of fact during periods in which oxygen consumption is very high (i.e. with a low DO concentration), as in the case of strong influent ammonia load, heterotrophic biomass uses a portion of the nitrate produced as electron acceptor. This aspect must be accounted for in the study of total nitrogen removal.

Hence, to better describe the two processes in the model, switching functions have been used (Henze *et al.*, 1987) in order to activate and deactivate kinetic equations for different environmental conditions. In the nitrification process a double saturation function was used to express the dependence of the autotrophic specific growth rate on both ammonia and oxygen. With respect to ammonia, the saturation function is characterised by a variable behaviour related to the instantaneous estimated concentration. During denitrification, biomass growth is regulated by a Monod kinetics under a double constraint for BOD_5 and nitrate. Moreover, as in nitrification, a switching function which inhibits anoxic growth in the presence of oxygen was introduced.

Model equations

In order to simulate the behaviour of ammonia and nitrate in every stage of the biological treatment, mass balances of the two components for each reactor have been performed. Production and consumption terms are added to hydraulic terms, related to mass transport, which take into account dilution and enriching phenomena. In the equations illustrated below, the inlet ammonia is removed from the system in nitrification, while produced nitrate is consumed in denitrification. Moreover, it was supposed that in the settling tank no reactions take place and that all reactors have a complete mixing behaviour.

In the following equations, "M" indicates ammonia, "N" nitrate and "C" BOD_5. The subscript is related to the corresponding section. Once the complete set of parameters included in the equations have been defined, these allow us to calculate the six unknown values of concentrations (M_1, N_1, C_1, M_e, N_e, C_e) in the oxidation tank and in the effluent.

Oxidation reactor balances *(M_1, N_1, C_1):*

$$\frac{dM_1}{dt}V = Q_i M_i + Q_{RIC} M_e - (Q_i + Q_{RIC}) M_1 - \frac{(1 - i_{NXV})}{Y_A} r_A V - i_{NXV}(r_{Hae} + r_{Han})V \qquad (1)$$

$$\frac{dN_1}{dt}V = Q_{RIC} N_e - (Q_i + Q_{RIC}) N_1 - \frac{(1 - Y_H)}{2.86 Y_H} r_{Han} V + \frac{1}{Y_A} r_A V \qquad (2)$$

$$\frac{dC_1}{dt}V = Q_i C_i + Q_{RIC} C_e - (Q_i + Q_{RIC}) C_1 - \frac{1}{Y_H}(r_{Hae} + r_{Han})V \qquad (3)$$

with:

$$r_A = \overline{\mu}_A \left(\frac{M_1}{K_{NH} + M_1}\right)\left(\frac{DO}{K_{O,A} + DO}\right) f_A X_V \qquad (4)$$

$$r_{Han} = \eta_g \cdot \overline{\mu}_H \left(\frac{N_1}{K_{NO} + N_1}\right)\left(\frac{K_{O,H}}{K_{O,H} + DO}\right)\left(\frac{C_1}{K_S + C_1}\right) f_H X_V \qquad (5)$$

$$r_{Hae} = \overline{\mu}_H \left(\frac{DO}{K_{O,H} + DO}\right)\left(\frac{C_1}{K_S + C_1}\right) f_H X_V \qquad (6)$$

Settling tank balance *(M_e, N_e, C_e):*

$$\frac{dM_e}{dt}V_{sed} = (Q_i + Q_{RIC})(M_1 - M_e) \tag{7}$$

$$\frac{dN_e}{dt}V_{sed} = (Q_i + Q_{RIC})(N_1 - N_e) \tag{8}$$

$$\frac{dC_e}{dt}V_{sed} = (Q_i + Q_{RIC})(C_1 - C_e) \tag{9}$$

The correction of the maximum specific growth rate with respect to the temperature is described as follows:

$$\bar{\mu}_H(T) = \bar{\mu}_H(20°C) \times 1.08^{(T-20)} \tag{10}$$

$$\bar{\mu}_A(T) = \bar{\mu}_A(20°C) \times 1.123^{(T-20)} \tag{11}$$

Simulation of an activated sludge system under alternatively aerobic and anoxic conditions, allows us to represent dynamics of carbon oxidation, nitrification and denitrification reactions. In general, influent load presents approximately daily periodical fluctuations, thus creating dynamic-stationary conditions (Zhao *et al.*, 1994b). In this situation it is possible to predict instantaneous concentration values and calculate daily mean values of the most important operating parameters. In particular, terms constituting BOD_5 and nitrogen balances are estimated; moreover, oxygen demand and biomass production can be evaluated.

As regards software operation, the simulation proceeds iteratively until concentration values estimated at the time $t = 24$ h coincide, within an error of 0.5 mg/l, with the values at time $t = 0$ h, starting from the initial conditions that are imposed to the algorithm. In this situation we can state that, with sufficient accuracy, dynamic-stationary conditions have been established.

Model calibration

To completely define the necessary variables for software operation, kinetic parameters must be fixed. Undoubtedly, experimental estimation of these values increases the accuracy that can be obtained, since these parameters are typical of biomass, environmental and feeding conditions of the plant: in particular, attention should be paid to the calculation of uptake rates under aerobic and anoxic conditions (Yang and Lin, 1998). However, when experimental data is lacking, literature values might be used.

Results

Numerical integration

A FORTRAN software has been implemented to solve the model equations through an integration technique for differential equations resolution (Henze *et al.*, 1987). For the generic concentration C, we can write the following expression in terms of finite differences:

$$C(t + \Delta t) = C(t) + \left(\frac{dC}{dt}\right)\Delta t \tag{12}$$

To avoid numerical errors, integration step Δt must be as small as possible, satisfying the following relation:

$$\Delta t < -C(t)\left(\frac{dC}{dt}\right)^{-1} \tag{13}$$

Writing extensively the balance for the generic component with concentration *C*, in differential form we have:

$$\frac{1}{C}\frac{dC}{dt} = \frac{I_C - U_C + P_C - K_C}{V \cdot C} \tag{14}$$

where I_C and U_C represent transport terms (input and output), while P_C and K_C represent production and consumption terms of the specified component. By substituting the second member of Eq. (13) with its expression given by Eq. (14) and neglecting positive balance terms (production and input) it follows that:

$$\Delta t < \frac{V \cdot C}{U_C + K_C} = \theta_H(C) \tag{15}$$

with $\theta_H(C)$ representing mean retention time in the control volume. In this way, we can estimate an upper limit for the integration time step. We shall obtain a few minutes limit (5–10 min.) in case we adopt mean values for the above mentioned components. The choice of integration time step is very important, in particular for several days' simulations. In fact, it is necessary to choose an integration interval small with respect to hydraulic retention time, but not so small as to allow the number of iterations to explode. In our case, as the investigation time interval never exceeds 2 or 3 days, a value $\Delta t \approx 3$ minutes can be selected, producing nearly 10^3 iterations.

Input and output

Because intermittent aeration is a dynamic process, it generates continuous concentration variations; all input values representing influent flow rate, organic carbon and total nitrogen concentrations, play an important role.

Input values consist of: time (h), flow (mc/d), BOD_5 and TKN (mg/l) expressed as time series related to the integration step. Besides the values of influent parameters, kinetic and design parameters are also displayed together with their default values. Of course these values can be modified and saved as defaults for subsequent simulations. In particular, heterotrophic and autotrophic biomass kinetic constants, plant design parameters and operation parameters are requested. An example of input and output display is shown in Table 1.

Moreover, upper limits (set-point values) for aerobic phase total nitrogen concentration and anoxic phase ammonia concentration are requested, to maximise total nitrogen removal and to avoid excessive ammonia concentration in the effluent, respectively (Table 2). Lower limits are also imposed to nitrate and ammonia (equal to 0.5 mgN/l) during the anoxic and the aerobic phase, respectively, to complete denitrification and nitrification processes. Besides, the minimum single phase duration is set at 45 minutes to avoid the system switching from ON to OFF mode too frequently during ammonia peaks.

At the end of execution, output values are: concentration values, ammonia to total nitrogen ratio, aeration daily fraction, and total removal efficiencies. Figure 1 reproduces trends, as a function of time, of influent loads, oxidation tank and effluent concentrations, as displayed in the output file of the model. All estimated values are reported in the output file (Table 3).

Conclusions

As to the treatment efficiency, intermittent aeration can allow us to meet the effluent nitrogen standards fixed by the European Directive 91/271, particularly in municipal small or

Table 1 Typical input display of the model

Heterotrophic biomass	
Max specific growth rate	MUHm = 3.50 1/d
Growth yield	YH = 0.60 mgVSS/mgBOD_5
Limiting BOD_5	Ks = 25.00 mgBOD_5/l
Limiting DO	KoH = 0.15 mgDO/l
Endogenous rate	bH = 0.08 1/d
Anox. growth corrective coeff.	etag = 0.60
Limiting NO_3-N	Kno = 1.00 mgNO_3-N/l
Autotrophic biomass	
Max specific growth rate	MUAm = 0.28 1/d
Growth yield	YA = 0.10 mgVSS/mgNH_4-N
Limiting NH_4-N	Knh = 1.00 mgNH_4-N/l
Limiting DO	KoA = 0.18 mgDO/l
Endogenous rate	bA = 0.04 1/d
Influent characterisation (fractions of TKN)	
Ammonia	fNa = 0.67
Unbiodegradable soluble N	fNous = 0.05
Unbiodegradable particulate N	fNoup = 0.10
BOD_5/BOD ratio	fC = 0.66
Plant design parameters	
Oxidation tank volume	V = 4690.00 mc
Settling tank volume	Vsed = 2671.00 mc
Recycle flow	Qr = 17000.00 mc/d
Safety factor	FS = 1.2
Operating parameters	
Biomass concentration	Xv = 3000.00 mgVSS/l
Operating temperature	T = 22.0°C
Aerobic phase DO	DOae = 1.00 mgDO/l

Table 2 Set-point input display

Set-point values	
Aerobic phase Ntot upper limit	spNt = 15.00 mgN/l
Anoxic phase NH_4-N upper limit	spM = 10.00 mgN/l

medium-size plants where nitrogen removal has to be implemented. In such plants this operation strategy usually adopts fixed duration of phases, only controlling the final results obtained. A correct use of the technique would require costly on-line instrumentation in order to control nutrient concentrations or other related parameters (pH, ORP, DO, Carucci *et al.*, 1997).

The model proposed in this paper would allow us to regulate the phase duration during the day taking into account only the daily influent fluctuations of parameters, in order to optimise the plant performances with respect to either energy saving or to nitrogen removal. In such a way, knowing the daily influent variations (which are usually quite constant for the same plant, only depending on dry or wet weather conditions, or on work day or holiday) one can predict the best phase temporisation for that particular case.

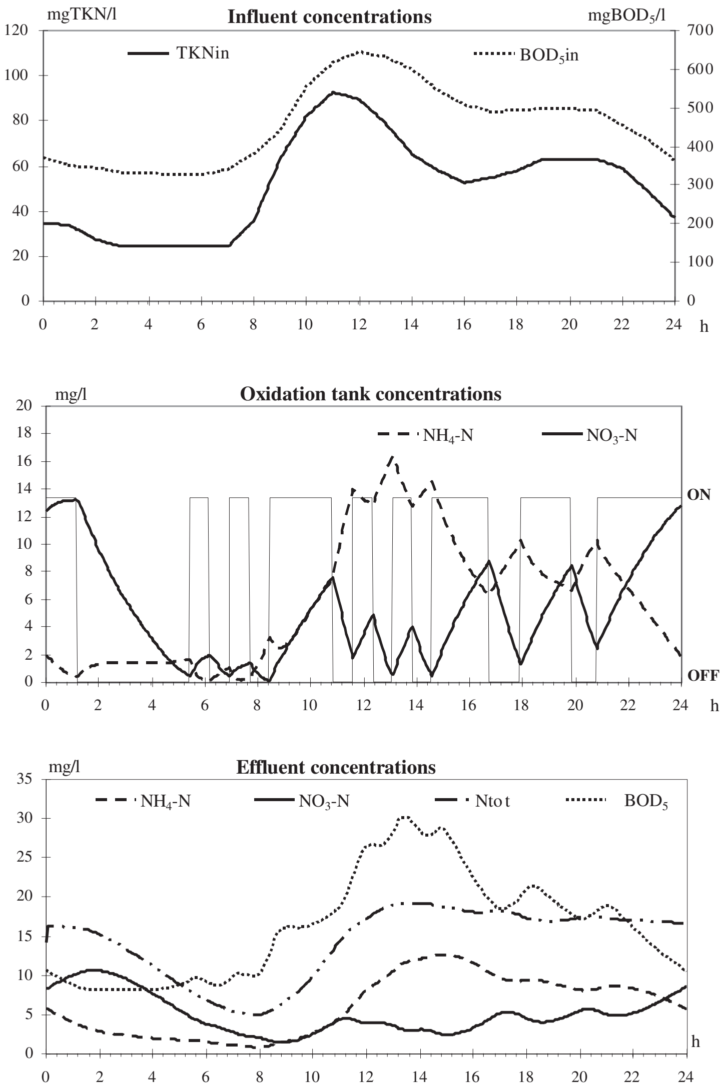

Figure 1 Output graphics of the model

Table 3 Typical output display of the model

Effluent concentrations and efficiencies	
Mean effluent BOD_5	= 11.83 mg/l
Mean effluent NH_4-N	= 4.15 mg/l
Mean effluent NO_3-N	= 6.07 mg/l
Mean effluent Ntot	= 12.66 mg/l
Effluent NH_4-N/Ntot ratio	= 32.80%
BOD removal efficiency	= 96.91%
Ntot removal efficiency	= 74.06%
Nitrification effic. (Nox/Nb(i))	= 44.85%
Denitrification effic. (Nden/Nox)	= 66.60%
Daily aeration fraction	= 0.558

References

Carucci, A., Rolle, E. and Smurra, P. (1997). Experiences of on-line control at a wastewater treatment plant for nitrogen removal. *Preprints of the 7th Int. Workshop on "Instrumentation, Control and Automation of Water and Wastewater Treatment and Transport Systems"*. Brighton, (UK), 6–9 July, pp. 459–465.

Carucci, A., Smurra, P., Dionisi, D. and Rolle, E. (1999). Optimising the operation of a full scale WWTP through a detailed wastewater and biomass characterisation. *3rd International Conference of ACE CR "WASTEWATER '99"*. Teplice (CK), 18–20 May, pp. 23–28.

Henze, M., Grady Jr, C.P.L., Gujer, W., Marais, G.v.R. and Matsuo, T. (1987). *Activated sludge model no. 1. IAWQ Scientific and Technical Report no. 1*, IAWQ London, UK.

Lukasse, L.J.S., Keesman, K.J. and Straten, G. Van (1997). Identification for model predictive control of biotechnological processes, case study: nitrogen removal in an activated sludge process. *Proc. 11th IFAC symposium on System Identification*, Fukuoka, Japan, pp. 1525–1530.

Thornberg, D.E., Nielsen, M.K. and Andersen, K.L. (1993). Nutrient removal: on-line measurements and control strategy. *Wat. Sci. Tech.*, **28**(11–12), 549–560.

Yang, J.Z. and Lin, K.C. (1998). Parameter determination for the intermittently aerated completely mixed (IACM) process. *Wat. Res.*, **32**(3), 856–864.

Zhao, H., Isaacs, S.H., Søeberg, H. and Kümmel, M. (1994a). A novel control strategy for improved nitrogen removal in an alternating activated sludge process–Part I. Process analysis. *Wat. Res.*, **28**(3), 521–534.

Zhao, H., Isaacs, S.H., Søeberg, H. and Kümmel, M. (1994b). A novel control strategy for improved nitrogen removal in an alternating activated sludge process–Part II. Control development *Wat. Res.*, **28**(3), 535–542.