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Performance optimization of an alternating oxidation ditch system by cycle timelength variation

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ABSTRACT

This paper presents a methodology for the optimization of the operation of an alternating oxidation ditch system, performing carbon oxidation–nitrification, denitrification and settling, through the use of a mathematical model and pilot testing. Measurements have been made in a pilot plant located in the Sanitary Engineering Research and Development Center of E.Y.D.A.P at Metamorphosis-Athens. Also, a mathematical model consisting of 1-dimensional mass balance (convection–dispersion) equations, based on the IAWPRC activated sludge model No. 1 was used. After the calibration and verification of the model with the experimental data, the optimization of the system's performance was achieved by testing operational cycles with different time lengths. Since carbon removal is way under the 91/271 E.U. directive's upper limits and since the ditch system has not been designed for phosphorous removal, the limits for nitrogen removal have been used for comparison. In this work's example, from the eight operational cycles that have been tested (120–400 min), only one (220 min–nitrification: 120 min/denitrification: 100 min), met fully the effluent criteria for nitrogen and minimum consumption of energy. However, the selection of the optimum operational cycle for each case is in the choice of the environmental engineer.

Keywords: Alternating oxidation ditch system; Optimization; Operational cycle; Mathematical model; Wastewater treatment; Nitrification–denitrification

1. Introduction

One of the well known Wastewater Treatment Systems (WTS) is the oxidation ditch process (with all its alternative types), which can be used in many situations all over the world. Operating in the extended aeration mode, it can achieve high treatment efficiency, together with a high degree of sludge stabilization. A popular type of the oxidation ditch is the alternating ditch system (or phased isolation ditch system), originally developed in Denmark. It is a continuous flow system, usually characterized by the use of two or three ditches, either with or without a separate secondary settlement tank [1–4].

In recent years, there has been a considerable renewed interest in the use of oxidation ditches. Many researchers have investigated its potential efficiency in treating wastewater. New approaches on the design and operation of this system have been made trying to optimize its capabilities concerning the removal of either carbon or nutrients, with field strategies such as simultaneous nitrification–denitrification [6,10,14]; new scheme configurations like oxidation ditches with vertical circulation [18] or scheme modifications regarding aeration

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or sedimentation [3,5]; modelling [9,17] and microbiological analysis [13].

A better understanding of the phased isolation ditch system behaviour, can lead to the solution of different kind of problems in its operation and in consequence to important reduction in operating costs, together with the increase of experience and knowledge in design. This paper investigates the existence of optimal operational cycles for an alternating oxidation ditch system that can meet the effluent criteria of the E.U. directive 91/271 regarding carbon and nitrogen removal. It also shows that some standard phase time lengths (such as 2/3 for nitrification and 1/3 for denitrification of the total cycle time length) usually used in practice and mentioned in international literature, cannot work in all cases for the required effluent concentrations or for the minimum consumption of energy. This is done through the use of a mathematical model, which was originally developed for the prediction of the concentration of the water quality variables in a single oxidation ditch [16] and was later modified in order to be used for the simulation of an alternating oxidation ditch system [11,17]. The model is based on the IAWPRC Activated Sludge Model No. 1 [7], coupled with 1-D advection–dispersion equations for an open channel flow. The data used for the calibration and application of the model, have been collected from a pilot plant system installed in the Sanitary Engineering Research and Development Center (SERDC) of Water Corporation of Athens [11].

2. Materials and methods

2.1. The pilot plant

The pilot plant consists of two oxidation ditches, interconnected with a pipe of 10 cm in diameter (Fig. 1). Each ditch has a total water depth of 1.0 m, a total volume of approximately 60.0 m^3 and a typical oval ring configuration with a trapezoidal cross section and side wall slopes of 1:1. The ditches perform carbon oxidation, nitrification, denitrification and settling, operating in four different phases as aeration–nitrification basins, clarifiers or anoxic basins. The duration of each cycle is 3 h. The oxidation ditch configuration and operating cycle is presented in Fig. 1. The plant has no separate primary or secondary settlement tanks, neither separate sludge digestion tanks.

In the first phase (A) sewage flows into the first ditch (OD1), where aeration is applied and carbon oxidation and nitrification occurs. Wastewater circulates in the ditch with an average flow velocity (u) of ~0.30–0.35 m s^{-1} and then enters into the second ditch (OD2) through the connecting pipe. In OD2, settling occurs and treated effluent exits via the outlet weir. The duration of phase A is 60 min. In the second phase (B) sewage enters into the settled sludge layer of OD2 (occupying the lower 0.30–0.40 m of the ditch), forms a bottom and very slow moving current, (where denitrification and settling occurs) and exits via the outlet weir. In OD1, where there is no inlet or outlet flow, the mixed liquor tranquillises, i.e., starts to settle without moving horizontally. The duration of phase B is 30 min. Phases C and D are mirrors of A and B, with the sewage entering into OD2 and OD1, respectively.

The system does not involve sludge recirculation. Sludge wasting, as mixed liquor, is accomplished directly from the interconnecting pipe, downstream of the aerated ditch, by means of a discharge valve.

Two horizontal brush aerators (rotors) are installed in each tank having different oxygenation capacities. The first rotor has a two-speed motor, while the second has a single-speed motor. The actual oxygenation capacities of the two rotors were measured in situ and aeration curves have been derived [8]. The Standard Oxygen Transfer Rates were calculated equal to 8.32 and 6.34 kg O_2 h^{-1} for the high and low speed of the first rotor, respectively, and 9.51 kg O_2 h^{-1} for the second rotor.

2.2. Experimental methods

Measurements of dissolved oxygen (DO) concentrations, to be used in the calibration of the model, were

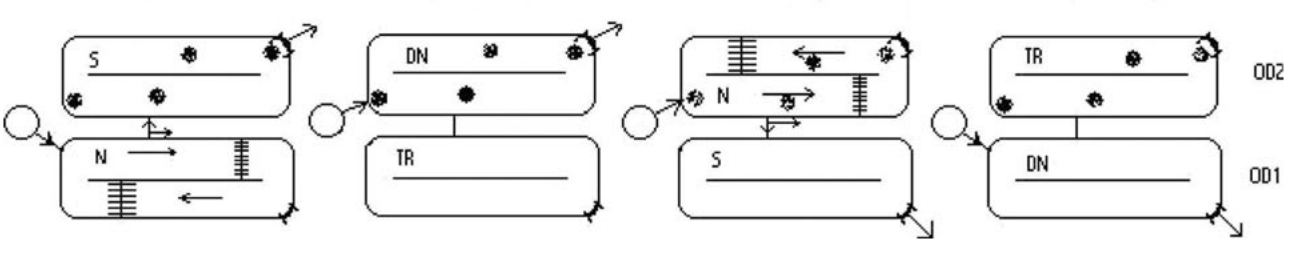

Fig. 1. Operational cycle of the oxidation ditch system: S = settling; N = nitrification; TR = tranquillisation-settling of mixed liquor, DN = denitrification.

made with a portable DO meter. The measurements were taken along the mid-width axis of the aerated ditch, at 50% of the depth. The duration of each series of experiments was ~5 min.

Process performance characteristics, including temperature, pH, BOD_5, COD, MLSS, MLVSS, SS, DSVI, TKN, NH_4–N, NO_x–N and alkalinity have been measured daily for a period of 16 mon. The experimental methods and procedures are presented elsewhere [11].

2.3. The mathematical model

2.3.1. The equations of the model

The mathematical model consists of mass balance equations [15] for the 13 water quality variables reported in the IWA Activated Sludge Model No. 1 or ASM1 [7], coupled with hydrodynamic effects.

Each of the two oxidation ditches is segmented into NI = 10 control volumes, as shown in Fig. 2. Equation (1) is integrated for each of the 13 water quality variables, over each of the 2 × 10 = 20 control volumes (using hybrid differences for Φ, central differences for the derivative of Φ and explicit forward time differences) to derive the 20 × 13 = 260 final difference equations of the model.

The mass balance equations are derived by applying the mass conservation principle to a small, finite control volume within the flow and are of the form:

$$\frac{\partial \Phi}{\partial t} + \frac{\partial (u\Phi)}{\partial z} = \frac{\partial}{\partial z} E\left(\frac{\partial \Phi}{\partial z}\right) + r_i \tag{1}$$

where Φ = the concentration of the variable (g COD m^{-3}); z = the distance from the inlet section (m); u = the average velocity in the ditch (m day^{-1}) and E = the dispersion coefficient (m^2 day^{-1}).

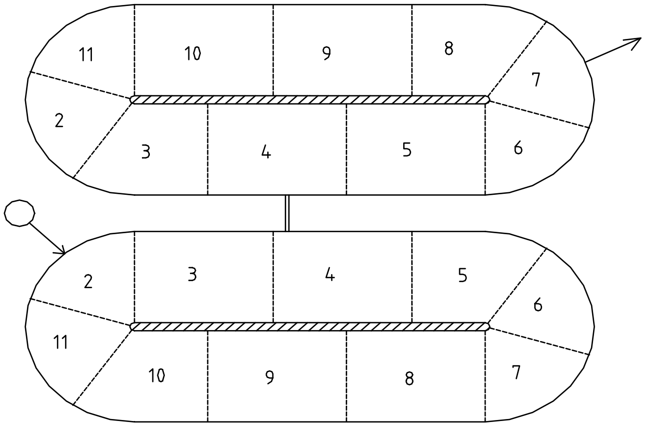

Fig. 2. Schematic presentation of the oxidation ditch system.

The source term ri, which represents the sum of all conversion rates for each biological variable i, can be written according to the ASM1 as follows:

$$r_i = \sum v_{ij}\rho_j \tag{2}$$

where v_{ij} is the stoichiometric coefficients, which set out the mass relationships between the components of the individual processes, whose rates are denoted by ρ_j (g COD m^{-3} day^{-1}).

2.3.2. Boundary conditions

The treatment of boundaries is performed as described in Stamou (1997) and Stamou et al. (1999), [16,17]. At the inlet and outlet control volumes, the equations of the model are simply modified to account for additional inlet and outlet mass fluxes, respectively. At the control volumes, where the rotors are located (see Fig. 2, control volumes 5 and 10) the DO equation is modified by adding an oxygen mass flux equal to the aeration capacity of the rotor, C_{ROT} (gO_2 h^{-1}).

For the operation of surplus sludge the following procedure is applied: The MLSS concentration X (g m^{-3})– which is equal to the sum of all particulate components concentrations X_i of the model – at the outlet of the aerated ditch, is compared to a preset value (X_{SET}). When X exceeds X_{SET} the discharge valve of the interconnecting pipe is activated to remove the surplus sludge from the system and to maintain X at the desired level (X_{SET}). The average sludge age of the system SRT (days) is fixed to a desired value (SRT_{SET}). This condition permits the calculation of the surplus flow rate.

2.3.3. Calibration of the model under steady state conditions

The calibration procedure of the model refers to the determination of the values of E, α and β. The values of the dispersion coefficient, E, and the correction factors α and β [12] of the equation of the aeration equipment (rotors), have been determined equal to E = 170,000 m^2 day^{-1}, β = 0.85 and α = 0.3 and 0.825, for the operation of the rotors in the low and high speed, respectively [11,17]. The values of the applied stoichiometric and kinetic parameters of the model have been determined experimentally or taken from the literature and are presented in Table 1.

2.3.4. Verification of the model

After calibration, the next step was the verification of the model. To achieve this, the model has been applied to each month of the experimental period and its results have been compared with measured monthly average effluent values from the pilot plant.

Table 1
Values of the stoichiometric and kinetic parameters used in the model

Measured		Taken from literature
$Y_H = 0.67$ (gCOD gCOD^{-1})	$n_g = 0.74$ (–)	$Y_A = 0.24$ (gCOD gN^{-1})
$\mu_H = 1.3$ (day^{-1})	$n_h = 0.30$ (–)	$K_{NO} = 0.5$ (gNO$_3$–N m^{-3})
$K_s = 26$ (gCOD m^{-3})	$\mu_A = 0.19$ (day^{-1})	$K_{OH} = 0.25$ (gO$_2$ m^{-3})
$b_H = 0.13$ (day^{-1})		$K_{OA} = 1.5$ (gO$_2$ m^{-3})
$K_{NH} = 0.65$ (gNH$_3$–N m^{-3})		$K_a = 0.08$ (m^3 COD (g day)$^{-1}$)
$i_{XB} = 0.054$ (gN gCOD^{-1})		$K_h = 2.0$ (gCOD (gCOD day)$^{-1}$)
$b_A = 0.06$ (day^{-1})		$K_X = 0.02$ (gCOD gCOD^{-1})

Results showed that predicted effluent concentration values were in a very good agreement with experimental values (Table 2). Similarly, good agreement has been found between the measured and predicted concentration values of MLSS in the ditches and the predicted surplus sludge flow rates [11,17].

3. Optimum operational cycles

Having proved the validity of the mathematical model to simulate system performance, we then used the model to investigate the existence of optimum operational cycles that would achieve the desired effluent standards without wasting the capacity of a particular cycle, i.e., too long aeration period.

To achieve this, the predicted profiles of nitrogen from the model and the fixed limits of the E.U. directive 91/271 for total nitrogen in the effluent, have been used. Nitrogen was selected for comparison, since BOD or COD effluent values in such an oxidation ditch system are way down the E.U. limits and the specific plant was not designed for phosphorous removal.

The operational cycles can be found by trial and error using mathematical models like the one presented herein. The engineer can choose the optimum cycle among the "candidate" cycles, taking into concern all the plant's functional parameters (e.g. nutrients removal) and costs (like the cost of aeration etc.).

It is well known that the directive 91/271 of E.U., faces nitrogen in the effluent as the total concentration of all nitrogen forms and fixes the upper limit to 10 mg/l of total N, for disposal in sensitive recipients. If therefore one makes the relatively conservative assumption, that

Table 2
Comparison between predicted monthly average effluent concentration values and measurements in the oxidation ditch system (soluble COD, NH_4–N and NO_x–N)

Month	Soluble COD (S_S) (gCOD m^{-3})		NH_4–N (SNH) (gN m^{-3})		NO_X–N (SNO) (gN m^{-3})	
	Measured	Model	Measured	Model	Measured	Model
1	76.6	70	32.7	25	<1	0.3
2	58.5	62	7.2	9	1.6	2.2
3[a]	42.3	46	1	2.5	5	4.4
4[a]	56.2	52	2.6	3.7	5	7
5	70	71.8	10.6	12	3	2
6	55.3	58.5	12	11	3	1
7	57.8	60	28.9	34	2.2	1
8	65.7	71	39	38	1.3	1.8
9	60	59	37.5	37	1.2	0.9
10[a]	41.7	44	<1	0.4	–	3
11[a]	38	40	<1	0.7	5.7	5.2
12[a]	49.6	49	<1	0.6	7.2	8.3
13[a]	30.7	32	1.4	1.4	5.9	3.2
14[a]	45	48	1.5	3	6.7	4
15[a]	52.4	55	4.7	4.8	8	6.4
16[a]	45.9	47	3.8	2.5	7.7	5.6

[a] With grey color are the months with high oxygen concentration (O_2 = 4–6 mg/l) in the aeration ditch and with black color are the months with low oxygen in the aeration ditch (O_2 = 1–1.5 mg/l).

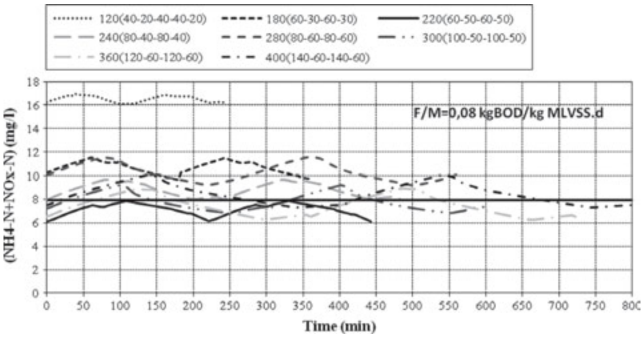

Fig. 3. Model predicted nitrogen (NH_4–N + NO_x–N) profiles, in one ditch of the system, for different durations of operational cycles and phases.

the concentration of dissolved organic nitrogen in the effluent of the system is 2 mg/l, then the sum of (NH_4–N + NO_x–N) must not exceed the limit of 8 mg N/l. The particulate organic nitrogen in the effluent can not be taken into consideration here, because it depends on the TSS concentration in the effluent and hence on the operation of the sedimentation ditch and not on the biological efficiency of the system.

In Fig. 3, different monthly average nitrogen profiles in the effluent of one ditch for two consecutive cycles predicted by the model, for various combinations of cycle times, (i.e., 2 × 220 = 440 min), are presented. The input data of the model for this example are average experimental values, taken from one month of the experimental period, with many measurements and thus better serve this case. These data are presented in Table 3.

Fig. 3 reveals, that an optimal operational cycle could be that of 220 (60, 50, 60, 50) min, with NO_x–N concentrations from about 0.2 to 3.7mg/l and NH_4–N concentrations from about 4.5 to 5.8 mg/l. Moreover, the model, gave values of dissolved organic nitrogen in the order of 0.2–0.7 mg/l. Apart from the 220 min cycle, acceptable could become also the cycles of 240, 300, 360 and perhaps that of 400 min. These last cycles however, have total aeration times of 160, 200, 240 and 280 min and hence larger corresponding consumption of energy than that of 220 min, with a total aeration time of 120 min/cycle.

Three observations came out from the investigation of the behaviour of the oxidation ditch system: The first refers to the duration of each phase in the total operation cycle. The optimal cycle of 220 min, is made up of 120 min for nitrification phase and 100 min for the denitrification phase. These time durations represent 0.545 and 0.455 of the total cycle duration, which are not the classic standard percentages of time durations of 0.66 (2/3) for nitrification and 0.33 (1/3) for denitrification [16], often used in such systems and proposed from practical experience. This shows that the usual standard percentages, cannot work in all cases to achieve required effluent concentrations or minimum consumption of energy.

The second observation resulted from a combined analysis of the model simulations and experimental results concerning the operational cycles. Given that the inflow remains the same, an increase of the total cycle time length resulted in an increase of NH_4-N concentration in the effluent—even in the group of cycles where the percentage of aeration time remains the same—due to the increased quantity of NH_4–N entering the system during the denitrification phases.

The third observation is, that for a given inflow, in cycles (like 120, 180, 240, 300 and 360 min), with the percentage time ratio 2/3 for aeration and 1/3 for denitrification, the increase of the total cycle time, resulted in a high increase of the NO_x–N concentration. This latter was due to incomplete denitrification because of the inadequate phase time (phases B and D). In cycles (like 220 and 280 min, in this example), with higher percentages for denitrification time, the increase of the total cycle time resulted in a significant reduction of NO_x–N concentration due to adequate time for denitrification. Nevertheless, this does not mean that for these last cycles the increase of the total cycle time decreases the sum of (NH_4–N + NO_x–N), as the increase of NH4–N is significant.

4. Conclusions

This work shows the existence, for an alternating oxidation ditch system performing carbon oxidation–nitrification, denitrification and settling, of several operational cycles with different time lengths that can meet the effluent criteria of the E.U. directive 91/271. The selection of the optimum operational cycle among

Table 3
Monthly input data of the model for this example

Flow (m^3 day^{-1})	SRT (day^{-1})	MLSS (g m^{-3})	MLVSS (g m^{-3})	COD_{in} (g m^{-3})	BOD_{in} (g m^{-3})	TKN_{in} (g m^{-3})	NH_4–N_{in} (g m^{-3})
49.92	39.47	4264	2983	629	274	56	39

them, for each case, is in the choice of the environmental engineer.

In this work's example a cycle with a total time length of 220 min (120 min for nitrification and 100 min for denitrification) seemed to be the best of those tested.

Model predicted profiles of total nitrogen (sum of NH_4–N + NO_x–N) have been compared with the E.U. directive 91/271 limits for total nitrogen in the effluent, to determine these operational cycles.

It has been shown that the standard phase time length percentages of 2/3 for nitrification and 1/3 for denitrification, cannot work in all cases for the required effluent concentrations or for the minimum consumption of energy.

An increase of the total cycle time length resulted in an increase of NH_4–N concentration due to the increased quantity of NH_4–N entering the system during the denitrification phases.

In cycles where the percentage time ratio for aeration and denitrification phases was the same (2/3 aeration and 1/3 denitrification), the increase of the total cycle time resulted in a high increase of NO_x–N concentration due to incomplete denitrification. In cycles with higher percentages of denitrification time, there is a significant reduction of NO_x–N concentration due to adequate time for denitrification. Nevertheless, this does not mean that for these last cycles the increase of the total cycle time decreases the sum of (NH_4–N + NO_x–N), as the increase of NH4–N is significant.

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