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MODELING AND IDENTIFICATION OF AN
ACTIVATED SLUDGE PROCESS

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MODELING AND IDENTIFICATION OF AN ACTIVATED SLUDGE PROCESS

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The activated sludge process is one of the major process units in a wastewater treatment plant. Dissolved oxygen (DO) must be available in order to maintain the microorganism activity. The DO dynamics is a crucial part of the reactor dynamical behaviour, as it reflects both physical and biological activities. In this work DO models are discussed in the light of identification experiments made on a full scale municipal wastewater treatment plant.

Introduction

The activated sludge unit is one of the major process units in a wastewater treatment system. Microorganisms in the activated sludge react with the organic pollutants in the wastewater and with oxygen dissolved in the water to produce more cell mass, carbon dioxide and water. The aerobic environment is achieved by the use of diffused air or mechanical aeration. The effluent of the reactor flows to a sedimentation basin, where the activated sludge is separated from the liquid phase, fig 1. A portion of the concentrated sludge is recycled in order to maintain enough mass of viable organisms in the system. Part of the settled sludge is wasted. The process effluent consists of the clarified overflow from the settler tank.

Dissolved oxygen (DO) dynamics is important to know for two major reasons. Firstly, the DO concentration has to be kept above a critical level, some 1-2 mg/l. Otherwise it is a growth limiting factor for the cell mass. For higher concentrations, the metabolism is independent of the DO level. Therefore it is important to keep the DO level low in order to save aeration power costs. Secondly, the DO concentration is related to biological activities. A reliable DO dynamical model can be used for estimation of biological parameters and organic loading, as DO sensors are among the few reliable on-line instruments available.

In the last few years, problems of wastewater treatment operations have received more attention than before. Noteworthy works on activated sludge models have been done, [1]-[3], and control problems have

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been formulated, [4]-[5]. Special conferences on automation and instrumentation in wastewater treatment systems have been arranged, [6]-[7], where dynamical modeling has been emphasized to some extent. For more details on biological models available, the reader is referred to [8].

Even if there are several mechanistic models available, the verification of these models remains an awkward problem. They are nonlinear, multivariable and space dependent. The hydraulics of the reactor as well as the dynamical behaviour of the settlers are poorly known. The nutrient is not a single component but several organic compounds of different types. The organism concentration actually represents a heterogeneous collection of different species. Moreover, it is unlikely that an on-line measurement of the concentrations of different compounds can be obtained with today's instrumentation. Therefore it is preferred here to take a "black-box" approach in the identification. Some important cause-effect relationships can be verified in order to get reasonable control models as well as more knowledge of the internal parameters. The verification of an internally descriptive model can thus be approached piecewise by drawing inferences from black-box results, as in [2]-[3].

Control of DO as a physical variable is not an advanced control problem, at least not for complete mix reactors, as soon as suitable sensors and actuators are available. The reason is that the oxygen transfer dynamics is much faster than hydraulic changes or the metabolism. DO control has been implemented in some plants, [9]-[12], and generally consists of digital or analog PI control. DO control, however, will be significantly more complex when the concentration is not uniformly distributed over the reactor.

In this paper, identification experiments are reported for a full scale municipal wastewater treatment plant. Three different input variables have been manipulated and several physical and chemical variables have been recorded. The process knowledge has been increased especially for oxygen transfer and plant hydraulics. Several spin-off results for future model building and operations have been achieved. The obtained model is sufficiently accurate to control the DO concentration, but a more accurate model is necessary before the model can be used to estimate internal biological parameters.

The Käppala Wastewater Treatment Plant

The identifications have been performed on a full scale municipal wastewater treatment plant at Käppala outside Stockholm. The plant serves the northern suburbs of Stockholm and was completed in 1969. The average dry-weather flow (1975) is about $1.3 \text{ m}^3/\text{sec}$. In addition to the activated sludge units, the plant has also chemical precipitation for phosphorus removal.

The dynamical experiments have been performed on one of the six parallel aerators in the plant. Each aerator has a volume of 6000 m^3 and a length of 100 m. Air is supplied by diffusers uniformly along the tank. The raw wastewater is fed at four positions between 30 and 60 m from the head end, a so-called step loading, see fig 1. The plant is equipped with a Siemens 304 computer for data acquisition.

Dissolved Oxygen Dynamics

The basic theory for oxygen transfer and DO uptake has been studied extensively, see e.g. [13]. Here the basic dynamics is presented for a complete mix reactor. More details are found in [8]. Referring to fig. 1 for the hydraulic flows, the mass balance for DO is

$$\frac{dc}{dt} = \frac{Q}{V} [c_i - (1+r)c] + k_1 u (c_s - c) - k_2 f_1(c) f_2(s, x) - k_3 x \quad (1)$$

where c = DO concentration; c_i = influent wastewater DO;
 c_s = DO saturation concentration;
 V = reactor volume; u = air flow rate;
 k_i = constants; $k_1 u$ = overall oxygen transfer coeff.;
 s = substrate conc.; x = microorganism conc.

The first term is the mass flow of DO. The second term models the oxygen transfer, i.e., the process when gaseous oxygen is transferred to the dissolved phase. According to Henry's law, the transfer rate is proportional to the difference between the saturation concentration and the actual DO concentration. The overall oxygen transfer coefficient is assumed to be proportional to the air flow rate. The third term in (1) is the oxygen uptake due to cell synthesis with f_2 new cells created per unit time. For small DO concentrations, the synthesis rate is limited by a factor f_1 . The last term in (1) is the endogeneous respiration (or decay) oxygen uptake.

Typically the time scale for the metabolism is considerably longer than that of oxygen transfer. The hydraulic detention time is longer

than the oxygen transfer as well. Therefore the substrate and organism concentrations can be assumed to be constant during one or two hours. A control system can take advantage of the different time modes of the system. In the identification, those differences can of course be used too.

Dissolved Oxygen Profiles

The actual plant is not a complete mix type and it is more adequate to describe the spatial distributions of DO, substrate and organisms with a dispersed plug flow model [8]. The air flow is uniformly distributed along the tank, and this fact makes the DO concentration strongly varying along the tank. Because of the high biological oxygen uptake rate, the DO level is low at the head end. The substrate concentration, and consequently the synthesis rate, decrease along the tank. Therefore, the DO concentration increases. A typical profile from the Käppala plant is shown in fig. 2.

With few DO probes available, it is crucial to locate them at the best positions. This would be where the DO concentration is most sensitive to changes in air flow rate. The sensitivity of DO profiles for plug flow reactors has been analyzed in [14]. The maximum sensitivity was found to be in the region where the slope of the profile has a maximum. This fact was verified during the identification experiments. According to figure 2, the best locations of the sensors is 60 to 90 m from the head end.

Nonlinearities

As the system is bilinear in c and u , the response time depends on the input amplitude. In different parts of the tank, the DO is different. For a given air flow rate change, the response time is the same throughout the reactor. However, the gain decreases towards the tail end.

Considering the numerical values of the parameters, the nonlinearities due to disturbances in the influent water or return sludge flow rates can be neglected. This is important because high input amplitudes are desirable due to the small gain for these inputs.

Experimental Conditions

Unlike other industrial processes, a wastewater treatment plant is hardly ever in steady state. Both the flow rate and the organic pollutant concentration of the influent are varying greatly. It is therefore

impossible to create ideal conditions for identification experiments. The influent chemical oxygen demand (COD) could not be measured on a regular basis, so the substrate influence on the DO could be only qualitatively estimated. It is impossible to measure the viable organism concentration. It is, however, reasonable to assume that variations in the organism concentration are related to variations in turbidity (MLSS) in a short time scale.

The influent water flow (Q), however, could be manipulated by re-directing the stream to parallel channels. The return sludge flow (r) was disturbed too. The water flows are considered disturbances to the DO while the air flow is the natural control input. The three inputs were disturbed both independently and simultaneously.

The settler is an integrated part of the activated sludge system. Water flow disturbances result in sludge settleability changes, and they are fed back into the reactor, through the return sludge flow, as MLSS changes. These variations will naturally obscure the results to some extent.

Data Handling and Identification

Experimental data were punched on paper tape on the on-line computer. The data has been analyzed and identified at the PDP 15/35 computer at the Department of Automatic Control, Lund. An interactive program IDPAC [15] has been used for the data analysis, parameter estimation as well as model analysis. The feature of interactivity has been of particular value here. As the process dynamics is known poorly, a large number of model structures have been tested and analyzed.

For the identification, the canonical Åström structure [16] has been used,

$$A(q^{-1}) y(t) = \sum_{i=1}^p B_i(q^{-1}) u_i(t) + \lambda C(q^{-1}) e(t) \quad (2)$$

where A, B and C are polynomials in the shift operator q. The parameters have been identified with the Maximum Likelihood (ML) method. Both the structure and the identification method are extensively described elsewhere, [17]-[19]. In the following paragraphs, the input-output relationships will be discussed one output at a time, although multivariable experiments were performed too. It is believed, that the process dynamics can be more simply described by this.

Air Flow Rate Disturbances

The air flow is the natural control input to the DO concentration. Some typical parameter models are shown in table 1.

Table 1. Model parameters for air flow rate input.

Expt	1	2	2	2
Case	1	2	3	4
Output	DO2 (84 m)	DO1 (64 m)	$\frac{1}{2}(\text{DO1}+\text{DO3})$ (64 m)	DO2 (84 m)
N	1840	405	405	405
a_1	-0.995 ± 0.001	-0.979 ± 0.003	-0.978 ± 0.003	-0.988 ± 0.002
$b_1^1 (*100)$	0.595 ± 0.044	0.985 ± 0.095	1.122 ± 0.093	1.017 ± 0.086
c_1^1	-0.641 ± 0.330	-0.564 ± 0.036	-0.518 ± 0.035	-0.244 ± 0.046
λ^1	0.206 ± 0.003	0.383 ± 0.013	0.335 ± 0.012	0.256 ± 0.009
Δt (s)	10	20	20	20
T (min)	33.2	15.4	14.7	28.7

N = number of samples; Δt = sampling time; T = time constant

The models are only of first order. Generally, only poor models of second order were found. The time constant is the inverse of the oxygen transfer coefficient, and is about 15 minutes for the signals DO 1 and DO 3 and about 30 minutes for DO 2. The results show that the oxygen transfer coefficient would be different at different locations. In fact, it varies with the water quality along the tank, [20], but such a change should give DO 2 a slightly smaller time constant than DO 1. Therefore the different time constants must depend on different degrees of mixing or air flow rates. Probably the pneumatic resistance in the diffusers around DO 2 is larger due to clogging.

In static calculations, the oxygen transfer coefficient was found to be 4 hr^{-1} , corresponding to 15 minutes time constant. Typical values [20] vary from 3.5 to 6 hr^{-1} .

The static gain in cases 1 and 4 are different because of different calibrations of the sensors. The values of λ and c_1 are quite similar for cases 2 and 3, as these sensors are located close to each other. The standard deviation of b_1 in case 1 is about half of that of the other cases, as the number of samples is about four times larger.

Plottings from air flow experiments are shown in figs. 3-7. The model error is quite large in fig. 7, but no better model could be found. The discrepancy is not due to sludge concentration or unintentional water flow variations, but could be due to influent COD variations.

In expt 1, a second order model was found for the DO 1 concentration with the time constants 11 minutes and 11 seconds. The result caused

confusion as it indicated that the DO sensor would be sensitive to gas bubbles on top of the dissolved oxygen. As the microorganisms can only utilize dissolved oxygen, the sensor would show unreliable values. The membrane of the probe was changed and a fast response could not be seen any more. The result, however, was an interesting spin-off. A failing membrane can be detected by a dynamical on-line test relatively easy. A static test can hardly reveal a poor membrane.

Influent Wastewater and Return Sludge Flow Rate Changes

For an increasing water flow rate, the DO concentration will decrease, primarily due to higher dilution. Two models for the influent water input are shown in table 2, cases 5-6. The time constants are

Table 2. Model parameters for water disturbances.

Expt	3	3	4
Case	5	6	7
Input	influent	influent	return flow
Output	DO 1 (66 m)	DO 2 (72 m)	DO 1 (66 m)
N	424	424	783
a_1	-0.969 ± 0.005	-0.978 ± 0.010	-0.993 ± 0.004
$b_1 (*100)$	-0.344 ± 0.031	-0.699 ± 0.199	-0.534 ± 0.330
c_1	-0.453 ± 0.042	-0.214 ± 0.056	-0.762 ± 0.035
$\lambda (*10)$	0.113 ± 0.004	0.542 ± 0.019	0.114 ± 0.003
Δt (s)	60	60	30
T (min)	32.1	45.6	71

different compared to the air flow input but also relative to each other. The reason is the hydraulics, which influence the time constants significantly. Assume that the tank can be described as a series of sub-reactors. A simple mass balance over each subreactor shows that there are two inputs to the DO concentration. The first one is the flow rate, which instantly changes the dilution, as the volume is constant. The second one is more significant in size but slower. It is the DO input from the preceding subreactor. The concentration transport from the head end to the sensor location determines the response time. In a complete mix reactor, this concentration transport is rapid and the time constant is determined by the oxygen transfer dynamics. For the actual part of the channel--between the DO sensors--the flow is close to plug flow with stream velocity of about 0.4 m/min. With the sensors separated 6 m in space, this means 15 minutes delay time, which can explain the difference in time constants.

Figs. 8-9 show the plottings from case 5. The model output error is not satisfactory, especially at the end of the experiment. By including unintentional MLSS and return sludge flow variations the model could be improved. The model error in the end, however, did not improve. Unmeasured COD variations could partly explain the model error. The most plausible reason, however, may be the flow measurement. The flow signal, fig. 8, shows some high spikes starting at 2.5 and 4 hrs, respectively. They may be caused by transients in the Parshall flume, and have no resemblance in the true reactor flow. The spikes contribute to wrong values of the input mean and the b_1 parameter.

The model for the return sludge flow rate input, case 7, has a much longer time constant than case 5. The hydraulics is again the reason. As the return sludge is entering the aerator at the head end (fig. 1), its transportation time to the DO sensor is longer than that of the raw wastewater. The results show that the flow cannot be purely plug flow, because then the transport time would be 4-6 hrs. Thus there is a significant dispersion in the head end part of the reactor. This has been verified by trace material studies.

Conclusions

The oxygen transfer rate has been identified and corresponds to a time constant of about 15 minutes. Load changes in terms of water flow or substrate concentration changes are clearly observed in the DO concentration. In closed loop control, the load changes are reflected in the air flow rate changes, a fact that has been verified by digital control of the DO in the plant. Information of the air flow variations will be used for the control of the biological reactions. Some important spin-offs have been found,

- * membrane deficiencies can be detected on-line
- * clogging or changing air flow resistances can be detected
- * hydraulic characteristics can be tested with available on-line DO probes

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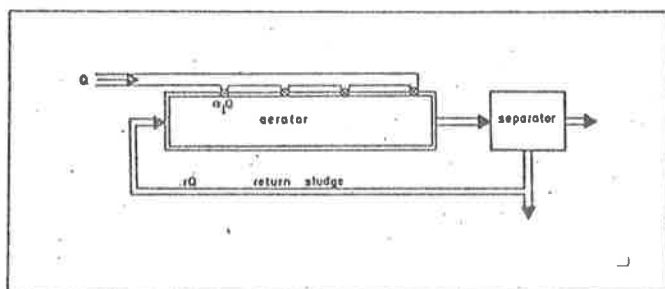


Fig. 1. Schematic flow diagram of the activated sludge process.

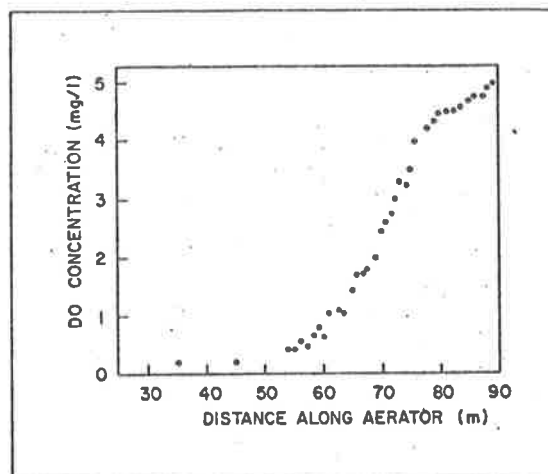


Fig. 2. Typical DO profile at the Käppala plant.

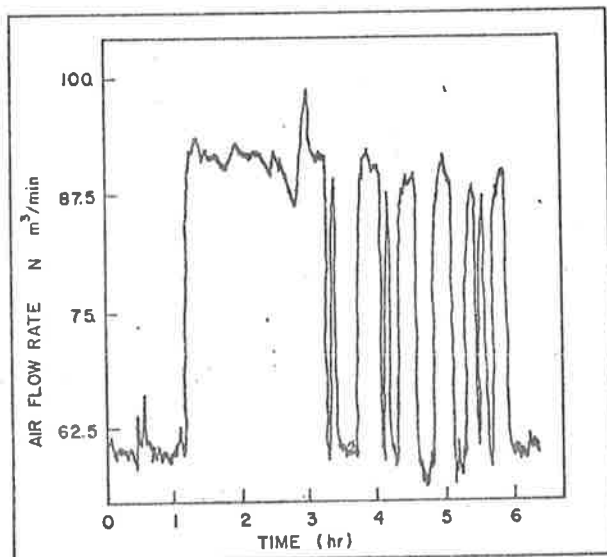


Fig. 3. Air flow rate input.

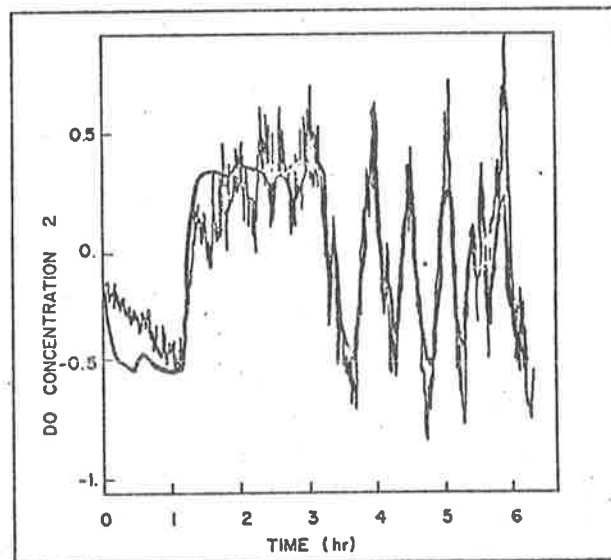


Fig. 4. Experimental DO output compared with a 1. order model output from the air input, fig. 3.

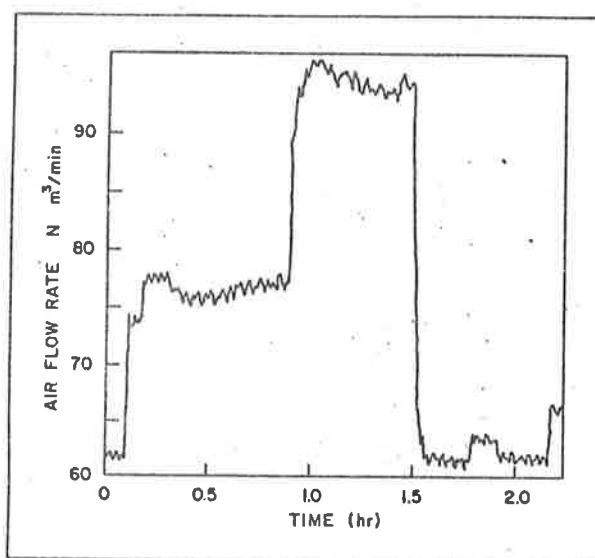


Fig. 5. Air flow input, expt 2.

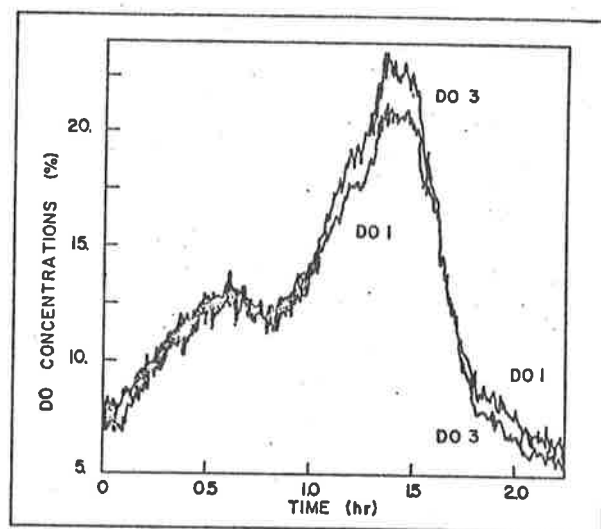


Fig. 6. Recordings of DO 1 and DO 3, expt 2.

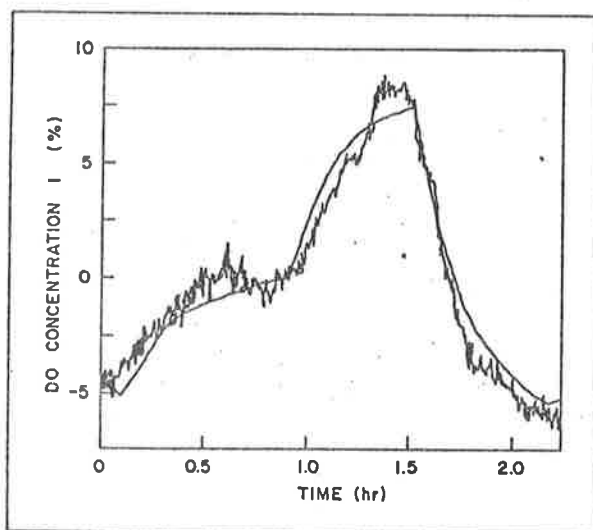


Fig. 7. Experimental DO output compared with a 1. order model output from the air input, fig 5, case 2.

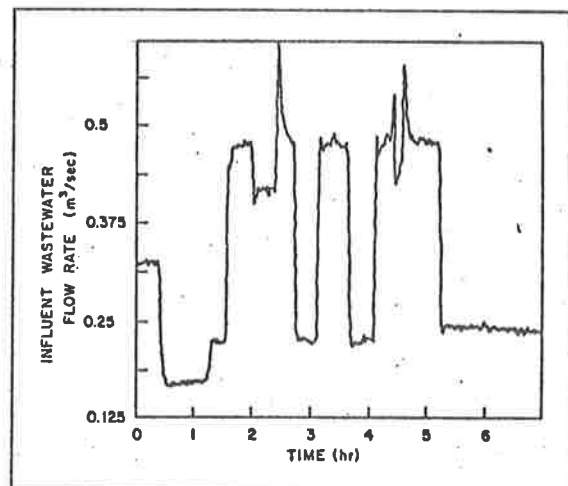


Fig. 8. Influent wastewater flow rate input, expt 3.

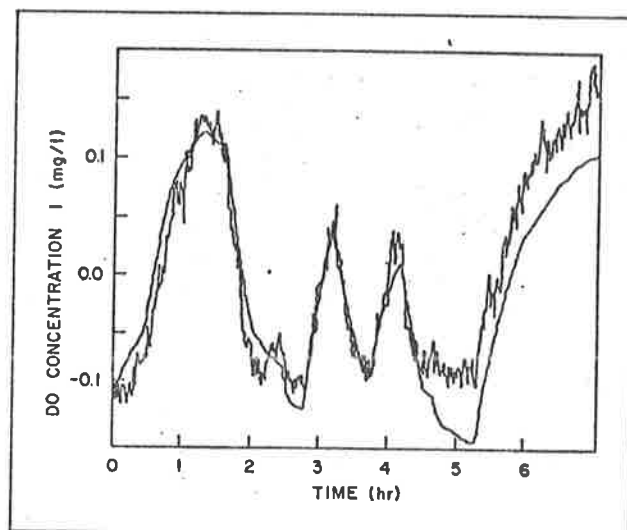


Fig. 9. Experimental DO output compared with a 1. order model output from the water flow input, fig. 8, case 5.