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AUTOMATIC CONTROL IN WASTEWATER TREATMENT PLANTS

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AUTOMATIC CONTROL IN WASTEWATER TREATMENT PLANTS

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Abstract. Process dynamics and control in biological wastewater treatment operations is considered. Particular emphasis has been put on the control of dissolved oxygen and its spatial distribution in activated sludge aerators. It is demonstrated how dissolved oxygen profiles can be used for the estimation of the biodegradable load. Aspects on the control of chemical precipitation are discussed as well.

INTRODUCTION

During the last two decades there has been a tremendous development of wastewater treatment plant construction in many countries. The investments in Sweden in the period from 1968 to 1977 were about 3500 M Sw Kr for sewage treatment plant and pump station constructions. In 1977 429 M Sw Kr were invested in new plants and pump stations. This is 26 % of the total investments for water and wastewater. In the same year 1977 more than 2200 M Sw Kr were charged for wastewater treatment. At the end of 1977 94 % of the Swedish population was served by biological or biological-chemical treatment. Some 2 % was served by only primary treatment and 4 % by mechanical-chemical or just chemical treatment. (VAV (1978)).

Now, with most of the plants constructed, the interest is gradually directed from plant design towards operation. A maximum use has to be made of existing plant constructions. The cost for wastewater treatment operations has increased considerably, from about 1.0 Sw Kr/m^3 in 1971 to about 3.50 Sw Kr/m^3 in 1978 (Hawerman (1978)). This gives a clear incentive to reduce the operational costs. It is getting recognized, that instrumentation and control has the potential for increasing effluent quality, enhancing treatment reliability and reducing treatment costs. This has been well documented in recent conferences, e.g. the symposia arranged by IAWPR in 1973 and 1977. Surveys of control and instrumentation in wastewater treatment can be found in Olsson (1977) and Molvar et al. (1976).

INSTRUMENTATION AND CONTROL

More than most industrial processes, municipal wastewater treatment plants are continually exposed to varying inputs and changing conditions. The plants must work under very different loading conditions. The flow rate as well as the concentration and composition of the sewage are varying on a short time basis as well as diurnally, weekly and monthly. This situation tends to produce a large variability of the effluent quality. Major disturbances such as rain storms, oils, grease, organic solvents and industrial chemical discharges contribute to upsets in plant operation, that is so commonly experienced. Internal streams in the plant are also creating large disturbances, such as recycle streams from sludge stabilization and thickening processes. To minimize the effect of disturbances the plants are often designed conservatively to meet peak loads, and this incurs higher-than-necessary capital and operating costs.

The motive to cut the operating costs is clear. Costs for energy, particularly for aeration and for chemical dosage have to be minimized under the condition, that the effluent quality is not deteriorating. These goals alone can motivate more instrumentation and control. Other objectives, such as improved plant reliability and control of major upsets with corresponding decreases in effluent-quality variability are other important reasons for control. It is of course desirable to operate a plant at its maximum efficiency. This would mean in the long run a smaller equipment and structure size and consequently less capital investment for a certain design flow rate.

During the last decade an extensive improvement of the chances for good operations has taken place. There are four major areas, that taken together have created a much more favourable situation for instrumentation and automatic control in wastewater treatment,

(1) improved process knowledge
(2) better instruments
(3) better control methods
(4) cheaper and more reliable computers.

Extensive studies on wastewater treatment plant dynamics have taken place in the last

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few years, see e.g. Olsson (1977), Stenström (1975), Fjeld (1978), Buhr et al. (1975), Molvar et al. (1976). This basic knowledge is fundamental for better operation of the systems. It is crucial to base operations on dynamical considerations and not only on static design tools. There is an increasing amount of on-line sensors, in-stream sensors or automatic analysers available, which are useful for continuous operation. The development of methods for mathematical model building, process identification, parameter estimation and advanced control technology should of course be reflected in the operations of wastewater treatment plants ultimately. The development of computers is unique. Therefore computerization seems natural. It is not a luxury, but rather a necessity in wastewater treatment operations.

Surveys of the wastewater treatment market today have shown (see e.g. Molvar et al. (1976)) that an average secondary treatment plant allocate only about 3 % of the construction costs to instrumentation. This figure is very low compared to other similar process industries. There are of course several explanations, why so little control and instrumentation has been implemented hitherto. Some of the reasons are:

(1) no profit incentive to produce high-quality effluent

(2) little or no economic penalty for poor-quality effluent

(3) lack of enough field-proven instruments for essential variables

(4) oversizing of plant capacity: environmental agencies seem to favour support of design costs but not operating costs. The design costs are not compared with operating costs in a proper way.

(5) general lack of familiarity with on-line instrumentation practices and needs

(6) a lack of education of civil engineers and plant designers in dynamics and control.

Sensors and measurement devices for the measurement of for instance flow and level, pH, consistency, density etc. have for a long time been used with success in process industries, often with equally difficult problems regarding measurement conditions as those existing in wastewater plants. It seems necessary to establish knowledge about the possibilities of instrumentation among designers. However, this will be of little use if not the interest and level of knowledge among wastewater plant operators is raised, and correspondingly good practices for the installation and maintenance of instruments are established. A practical impact of process control methods to wastewater treatment processes will only come when there is sufficient legal, moral and natural incentive to do so. Otherwise process control will not be deemed necessary (Roesler et al. (1977)).

DISSOLVED OXYGEN DYNAMICS AND CONTROL

The DO concentration is an essential variable in the activated sludge process. It is significant, both for the economy and for the biological activity of the reactor. The control of the DO concentration as a physical variable can be accomplished with superficial knowledge of the process dynamics. The coupling of DO to biological activity, however, makes the control much more of a challenge.

The choice of suitable DO concentration

It is not trivial - not even in a complete mix reactor - to determine an "optimal" DO level in the aerator. In a heterogeneous reactor the problem is even more difficult, and more advanced considerations have to be made.

The limiting concentration for the growth of organisms is different for different species of bacteria. It is lower for filamentous bacteria than for floc forming organisms. This is one of the reasons for sludge bulking, see Tomlinson (1976). The nitrifying bacteria (Nitrosomonas and Nitrobacter) have other limiting concentrations than the Heterotrophs. The limiting DO concentrations depend on the sludge age. With increasing sludge age a lower DO value can be accepted. In a process with nitrification there is seldom any bulking, caused by filamentous bacteria. The reason is, that the aeration has to be more intense in order to support both organic and nitrifying degradation of the sewage. If lack of oxygen should appear, then denitrification would appear first. Not until then, there is a risk for the growth of filamentous bacteria.

There is a complex relation between mixing and oxygen concentration. The degree of mixing will influence not only the DO concentration but also the floc formation and floc sizes. Therefore the degree of mixing is related to both sludge bulking and to the hydraulic dispersion in the reactor. The relation between oxygen addition and settling properties (sludge volume index, SVI) has been examined e.g. by Bosman et al. (1978). It is found, that the SVI will increase sharply for an increasing oxygen addition. This indicates that there is an ideal aeration value. Its low limit is determined by the growth rate of the organisms and its high limit depends on the SVI. It is not completely verified, if the increase of SVI is caused by the addition of oxygen as such or by the increasing mixing, that is related to the air flow increase. Still another factor contributing to the complexity of the problem is, that the effluent turbidity is often quite low at bulking sludge conditions. Therefore there is an optimization problem between clarifying and settling properties.

Nitrates can be used as complements or alternatives to oxygen both for energy saving and for treatment of certain industrial effluents. This is the background to the so called Krauss modification of the activated sludge process. Krauss treated reject water from digesters with nitrification. The water contained a large concentration of ammonia nitrogen. The nitrified water was lead to an activated sludge aerator, where usually filamentous bacteria were causing problems. In the process of nitrification/denitrification, where the nitrified water were returned to the process inlet, and where no oxygen were added, there were a low concentration of filamentous bacteria. Such an operation with an anoxic zone in the inlet area of the aerator has been tested in England, see Tomlinson (1978). The anoxic zone has also an influence on the pH. During nitrification nitrates and nitrites are formed and consequently the pH will decrease in waters with small buffer capacity. At pH about 5 the nitrification will be limited. Denitrification can increase the pH so nitrification will be favoured again.

Basic DO dynamics

The DO concentration of the aerator is determined by several physical, chemical and biological phenomena such as

- hydraulic transport of oxygen into and out of the aerator
- mass transfer of gaseous oxygen to dissolved oxygen
- oxygen utilization due to cell synthesis of floc forming bacteria (Heterotrophs)
- endogeneous respiration of floc forming organisms
- oxygen utilization of nitrification organisms (Nitrosomonas and Nitrobacter).

The hydraulic addition of oxygen can often be neglected in comparison with the mass transfer of gaseous oxygen to dissolved oxygen. A detailed derivation of the equations can be found elsewhere, e.g. in Olsson/Andrews (1978).

The interesting time scale for DO control is of the order of fractions of hours to a few hours. This means that changes in the organism culture or sludge growth can be neglected in this time scale. Long term effects, however, are also significant. Different control actions or concentration levels will favour different organism formations. This leads to varying settling and organic removal conditions. In order to test DO control systems it is crucial to consider also the long-term effects on the culture.

The natural control variable is the air flow. In enriched air or in pure oxygen systems the saturation concentration is higher, thus giving a larger mass transfer of oxygen.

There are several disturbances to the DO concentration such as

- hydraulic disturbances of influent wastewater or of the return sludge flow rate
- step feed changes
- organic disturbances
- ammonia disturbances
- toxic substances
- recycle streams from sludge handling units.

A more detailed description of the influence of the different disturbances is described in Olsson (1978 a).

Process identification of the DO dynamics

Process identification and parameter estimation has been an established field since several years. Its applicability in water quality systems has been demonstrated in several publications, such as Beck (1975, 1977), Beck/Young (1975), Olsson (1976 a,b), Olsson (1977), Sawaragi/Ikeda (1976) and Adeyemi et al. (1979).

The DO dynamics was examined by Maximum Likelihood (ML) process identification during a series of experiments from 1974 to 1977 at the Käppala wastewater treatment plant at Lidingö. The plant serves some 300 000 - 400 000 people of the northern suburbs of Stockholm. The average dry weather flow rate is about 1.3 m^3/sec. The details of the results have been published in e.g. Olsson/Hansson (1976 a,b).

The oxygen transfer was studied by manipulating the air flow rate manually. The hydraulic properties were studied by changing the return sludge flow rate. This in turn caused changes in the dilution of the sludge, so the oxygen uptake rate could be studied. This manipulation was difficult to make, however, and the changes in sludge concentration were "indirect" and not large enough to give good parameter estimates.

A couple of examples may illustrate the identification results. Figs. 1 and 2 show an experiment, where the influent flow rate has been manipulated according to Fig. 1. The flow rate changes have caused the mixed liquor suspended solids concentration to vary, Fig. 1. Both these variables will influence the DO concentration. The identified output of the deterministic part of the model is compared with the experimental measurement in Fig. 2. From this type of experiment also the dispersion of the aerator could be calculated indirectly.

The oxygen transfer has been determined in several experiments. Interesting enough, it did not change significantly between experiments separated one year in time. The value of the oxygen mass transfer stayed close to 4.3 (h^{-1}). The prediction error for a two minute prediction of the models usually stayed within 0.03 mg/l of the DO concentration.

No manual disturbances of influent organic or toxic disturbances in the full scale plants have been applied. The reason is, of course, that all natural disturbances have to be accepted. From a model building point of view only the biodegradable disturbances are relevant. Such disturbances cannot be measured directly on-line. Indirectly, however, they can be registered through the DO concentration changes. This is discussed in the next section.

DO control

Today there are several kinds of reliable and relatively reasonable DO sensors available. This makes a feedback DO control realistic also for quite small plants provided there are actuators suitable for control, such as continuously variable pumps or valves. Most of commercially available systems are based on analog PI regulators. They often give satisfactory results, but several conditions have to be satisfied. The problem to find a suitable set-point has already been mentioned. The amplitude of the noise and the measurement quality has to be such, that advanced filtering of the measurement data is not crucial for the control result. The time delays of the plant must not be long.

DO control based on digital computers has been applied in two plants in Sweden. A feasibility study was performed at the Käppala plant at Lidingö, Olsson/Hansson (1976 b). Later a more advanced control was implemented at Gävle, Gillblad/Olsson (1977). A very interesting study has been performed recently by the Sparling Division of Envirotech, Santa Clara California, see Wells/Williams (1978). The Swedish experiences have influenced the implementation. Two parallel tanks were tested during a six months period at the Fairfield water reclamation plant. Aerator number 2 was controlled manually giving the DO concentration a standard deviation of 1.8 mg/l. Aerator number 3 was controlled automatically by a digital controller. Its DO content had a standard deviation of 0.3 mg/l. The controller contained more complex features than a conventional PI controller, such as feedforward from the influent organic disturbances (a TOC analyser) and dead time compensation (Otto Smith controller). Sludge volume index (SVI) was regularly tested on both aerators and showed quite different behaviour. During a 5 month period the manually controlled aerator had a SVI of 199 ± 80 ml/g. The automatically controlled aerator had an SVI of 133 ± 41 ml/g. Moreover the automatically controlled aerator consumed about 18 % less air. Microscopic analysis showed that filamentous bacteria did not appear in the automatically controlled aerator, but created large problems in the manually controlled one. It was also noted, that the operator quite often increased his air flow rate while the automatic controller decreased the other air flow rate. The time delay of the system is causing difficulties for manual control, as the disturbances are detected too late, thus causing wrong corrections. A typical DO control result from the Käppala plant is shown in Fig. 3. Curve B shows the controlled DO concentration. The reference value is 3 mg/l with a standard deviation of 0.28 mg/l. Several experiences of DO control have been reported in Flanagan/Bracken (1977). Some of the results, however, may be critized. The evaluations of DO control sometimes have been made for quite short periods of time. For these tests it is impossible to make any reliable conclusions about microbial properties in the system.

The air flow signal in closed loop DO control gives a good indication of the biodegradable loading to the aerator. Even if the absolute value of the air flow does not give an absolute measure of the loading its variations make a good indication of the loading. Fig. 4 shows one example where hourly data of COD have been compared to the air flow rate on the Käppala activated sludge plant. As the waste comes from municipal sources the COD concentration is quite comparable to the biodegradable load, indicated by the air flow rate.

Practical difficulties in DO control

A measurement treatment of the signal from the DO sensor is important. The noise level caused by process and instrument is quite high and sophisticated filtering is often needed. Often large peaks in the noise create problems in conventional analog filtering. Then there are natural limitations of the control signal. The upper limit is determined by the compressor capacity and its lower limit is set by the minimum mixing requirement for the aerator. Several phenomena can cause problems due to the limited control authority. Some of them are discussed in Gillblad/Olsson (1978). The speed of the actuator is limited as the air pressure has to be kept within narrow constraints.

Many plants do not have an equipment that is suitable for control. Flanagan/Bracken (1977) have reported several problems connected with erroneous and unsuitable actuators. Also poor placement of DO sensors or poor mixers are reported. In some cases the control has to be performed by a valve that is too large. The control changes are simply too small. Most often the design of the plant is not flexible enough for easy control. A calculation is made stating that automatic control is profitable in plants with flow rates larger than 1 MGD ($\approx$0.045 m^3/sek) under the condition, that there is enough control flexibility and authority of the air system. Not only the economy but also the effluent water quality is favourably changed due to a smaller variability of the DO concentration.

DISSOLVED OXYGEN PROFILES

In most aerators the DO concentration is not uniform along the reactor. The DO concentration often has a characteristic profile with a relatively low concentration at the inlet area and a relatively high concentration towards the outlet. This results in practical as well as theoretical problems. The placement of the sensors has to be considered carefully. It is not easy to determine the desired DO concentration. Therefore an analysis of the meaning of the profile has to be made. It has been shown in Olsson/Andrews (1978) that the DO profile can determine whether the supply of oxygen is adequate or in excess of requirements. In fact the aeration tank can be used as an on-line respirometer.

Characterization of DO profiles

In an aerator with a uniform air distribution the DO concentration has a spatial variation, similar to Fig. 5. The oxygen content is close to zero at the inlet area, but often in excess close to the outlet. As the organisms mostly are satisfied with about 2 mg/l the question naturally arises, where to fix a suitable set-point. Normally only the total air flow and not its spatial distribution can be controlled. If the air flow were decreased to give a DO concentration of 2-3 mg/l close to the outlet, this would probably result in septic conditions close to the inlet. Therefore the choice of a suitable set-point is crucial, not to forget all the previous considerations. The literature of the dynamics of activated sludge processes could not give an answer of this question, when the DO control experiments at Käppala started in 1974. Every value of the DO set-point between 2 and 10 mg/l seemed reasonable. At that time the author started a research cooperation with professor John F Andrews at the University of Houston, USA. The problems of the DO profile have been considered in detail. Some static results are reported in Olsson/Andrews (1978). Dynamical properties are analysed in Olsson/Andrews (1977).

There are about five important features of the profile, see Fig. 5:

(1) the position of the maximum slope, which is related to organic or hydraulic load. The profile is pushed towards the outlet at higher loads and can be taken upstream by an increasing air flow rate.

(2) the value of the maximum slope is related to the specific growth of the organisms. The slope is high if the growth rate is high.

(3) the DO concentration at the outlet is relatively high if the synthesis is close to completion.

(4) the slope of the profile close to outlet is an essential information. It is directly related to the degree of completion of the cell synthesis. If it is close to completion the profile is almost horizontal. Otherwize the slope is more or less positive. The slope gives a significant information about the load and is in fact a more relevant information than the absolute value of the DO concentration at the outlet. This means that the slope is a more significant information than the absolute value of the DO concentration. This is the reason why many plants demand high excess DO concentration at the outlet. The real air flow demand is not directly related to the DO concentration at the outlet but its slope.

(5) The curvature of the profile between the maximum slope and the outlet can be described with a second derivative in space. The sign of this derivative is related to the load, the growth rate, and the degree of completion of the reactions.

A DO profile has the same qualitative appearance if nitrification occurs. The air flow, however, must be significantly increased. There are experiences from e.g. the South West treatment plant in Chicago showing that the air flow has to be twice as high during nitrification conditions compared to only organic removal. This observation can be clearly verified in theoretical models. Fig. 6 shows the DO profile with a combination of organic removal and nitrification in a plug flow aerator. The hydraulic dispersion will affect the DO profile. With a higher dispersion the gradients are attenuated, but all the qualitative conclusions about the meaning of the profile are still valid.

DO profile dynamics

The information from the profile characteristics is important for the operation of an activated sludge process. It is clear that different static loads will infiucence the profile. Normally, however, a wastewater treatment plant is never in a stationary condition, so in all operations the dynamics has to be considered.

As a basis for the following discussion an activated sludge process consisting of four subreactors in series has been modelled. The model contains organic removal and no nitrification. Process variables in each subreactor are soluble substrate concentration, stored mass (as a result of biosorption), living organisms, inert organisms and dissolved oxygen, see Olsson (1975). In the simulations the return sludge concentration has been assumed to be constant. This is a reasonable simplification as long as the return sludge flow rate is kept constant and the sludge buffer volume in the settler is positive. The disturbances of influent wastewater flow rate and BOD concentration are sinusoidal and in phase with each other. The amplitudes are 25 % around the average values. This gives a load variation to the plant from 56 % to 156 % of the average load. In the first simulation presented there is no air flow control, i.e. the air flow rate is constant. Then all DO concentrations are decreasing as a result of a decreasing load and vice versa, Figs. 7 and 8. It is instructive to represent the DO concentrations in another diagram, shown as functions of space with time as a parameter, Fig. 9. The DO profile is pushed downstream for an increasing load. The profile is represented by two variables, the slope

$$d_{43} = c_4 - c_3$$

and an estimate of the second spatial derivative of the profile towards the outlet,

$$d_{42} = c_4 - 2c_3 + c_2$$

where

c_i = the DO concentration in subreactor No i.

It is desirable that d_{42} is negative. For high loads it tends to positive values. The variations of d_{43} and d_{42} are shown in Fig. 10 and should be compared with the load variation, Fig. 7. It is obvious that d_{42} is a very sensitive measure of the biodegradable load.

Earlier it has been shown that the specific oxygen utilization rate (SCOUR) is a good measure of the biodegradable load to an aerator, see Stenstrom (1975). Fig. 11 shows how SCOUR is varying as a function of time for the different subreactors. The SCOUR profile, shown in Fig. 12 can also be used to show the biodegradable load. A comparison between the Figs. 12 and 10 demonstrates that the DO profile is as good an indication of the load as the SCOUR profile. The DO profile, however, is a much easier measure to handle. There is no need to have a good measure of the living organism concentration as in SCOUR.

DO profile during control

Assume that the concentration c_3 is controlled by the total air flow rate. The concentration c_3 is chosen for control because it is more sensitive to load variations compared with c_4, see Fig. 8. The controller in this case is a discrete time PD controller, i.e. both the DO concentration and its time derivative are used as a basis for control. A feedforward signal is added to the controller from the influent flow rate. This is due to the time delay in the process as well as in the discrete controller.

It has not been attempted to optimize the control. Instead a cautious air flow change has been applied, fig. 13. The control does not activate any air flow constraints, so the air flow signal better reflects the organic load to the plant. The control is, however, good enough to illustrate the point. Fig. 13 shows, that all the DO concentration variations - not only c_3 - are smaller than in the uncontrolled case. This means, that the profile changes are smaller as well. In Fig. 14 d_{42} is negative all the time, indicating a satisfactory completion of the synthesis. Still d_{43} and d_{42} indicate the load variations, like the air flow change. The advantage of using the profile characteristics instead of the air flow rate is obvious. The values of d_{42} and d_{43} can be given physical interpretations, directly related to the oxygen uptake rate. Moreover, the air flow signal is often limited, so it does not give a true indication of the load variation.

A practical demonstration of the DO profile is shown in Fig 3. Two DO sensors were coupled to the computer at Käppala, one at 80 m downstream and the other at 90 m downstream (total aerator length is 100 m). The DO concentration at 80 m was controlled at 3.0±0.28 mg/l. As in Fig. 14 the variations of the air flow rate (curve D) show the load variations of the plant. The air flow is clearly correlated to the slope of the DO concentration, c(90) - c(80), curve C. It may be hazardous to differentiate between two noisy signals, and calibration errors may cause further problems. In this case, however, the difference is sizeable and varies between about 1.2 mg/l to about 2.5 mg/l, i.e. a factor of two between smallest and largest difference. Therefore the accuracy can be satisfactory.

CHEMICAL PRECIPITATION CONTROL

Most of the Swedish wastewater treatment plants are supplied with chemical precipitation units. Even if much interest is turning into operating costs for chemicals and sludge handling control of chemical dosage is rarely used. If it is done at all it is on a primitive basis.

Usually the operating experiences of chemical precipitation are quite favourable and 95 % reduction of the phosphorus content is common. As a secondary result of post-precipitation suspended BOD can be further reduced. Due to the good operating results of chemical precipitation it is easy to be mislead by the results. Very often an excess dosage of chemicals has been used to compensate for poor operation of the biological processes. Therefore the operating costs have been unnecessary high in many biological-chemical treatment plants.

Chemical dosage control

The primary measure for chemical dosage is pH, particularly when metal salts are used as chemicals. Alcalinity is also important information, not only for lime precipitation, as it determines the buffer capacity of the water. Of course, it would be most desirable to know the concentrations of different phosphates but other values than the total phosphorus concentration are unrealistic to achieve.

Current control practice can be divided into two categories. In one the dosage is flow proportional and the dosage ratio is updated manually. The same technique is used both for phosphorus reduction and for sludge conditioning. In the other type of control there is a feed-forward control of the dosage from the flow rate. The signal from e.g. a pH sensor is fed back in order to make an adjustment of the dosage. A complementary measure of the effluent water turbidity or total phosphorus content can be made.

The coupling between nitrification and chemical dosage

There is no particular demand of nitrogen removal in Swedish wastewater treatment plants. Nevertheless nitrification has been observed in and purposefully tried in several Swedish plants. This has resulted in interesting spin-off effects of the dosage of chemicals for phosphorus removal. It is well known, that nitrification can give a lower chemical dosage, see Sharma/Ahlert (1977). In order to give an optimal precipitation pH must be very well defined. Often his pH is reached by an excess dosage of chemicals. This extra dosage is determined by the alcalinity of the water to a large extent. Biological nitrification results in a decrease of the bicarbonate concentration of 8.3 mg per mg oxidized ammonia nitrogen. If the influent raw wastewater has excess alcalinity the nitrification will therefore be advantageous for chemical precipitation. The decreasing demand for dosage as a result of nitrification has been demonstrated in several plants e.g. in Himmersfjärden (Larsson (1975)), in Örebro (Isgård et al (1974)), and in Huskvarna (Strandsäter (1978)).

It is an interesting optimization problem to weight the cost for increasing aeration to achieve nitrification (both a longer sludge age and a higher air flow rate) against the decreasing costs for chemicals. Such costs have been considered in Grönqvist et al (1978). This study showed, that the cost to increase the sludge age from 5 to 20 days is quite reasonable, between 5 and 10 %. This is easily compensated by the decreased demand for chemicals and the reduction of sludge treatment costs.

Recirculation of chemical sludge

Already in the sixties Thomas (1972) observed that chemicals could be saved at simultaneous precipitation if waste (iron) sludge was recirculated to the influent wastewater. The adsorbtion capacity for phosphorus in the chemical sludge could increase with an increasing phosphorus concentration in the influent sewage. This could be explained by theories for physical-chemical adsorbtion. Humenick/Kaufmann (1972) performed experiments to recirculate lime or aluminum sludge from post-precipiation to the aerator with similar results.

Different experiments with two stage precipitation have been performed recently in Sweden. A summary is made by Hultman (1978). Several different flow patterns have been tried. Combinations of simultaneous precipitation and post-precipitation, recirculation of sludge from post-precipitation to the aerator, or of post-precipitated sludge to the influent sewage have been tried. The results have been favouable. The phosphorus reduction is made more complete before the post-precipitation stage. This will save chemicals, reduce the amount of chemical sludge and decrease the effluent water phosphorus content.

CONCLUSIONS

There is a large need for improved knowledge of process dynamics for both biological waste reduction and chemical precipitation. This should be used for better understanding of operational practice. There is a need for a whole spectrum of models, ranging from simple but accurate models for on-line control to structured models with a great detail. The latter type of models has to be a base for better understanding. The DO profile may be a good example of this. In order to understand the meaning of the DO profile quite a structured model was needed. On the other hand, when the understanding has been achieved, a fairly simple model of just few parameters can be used to represent the dynamics in the aerator.

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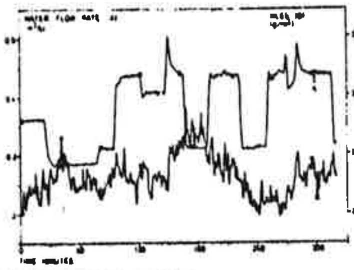

Fig. 1. Hydraulic disturbance signal in the Käppala wastewater treatment plant. The water flow was manipulated, causing the sludge concentration to vary.

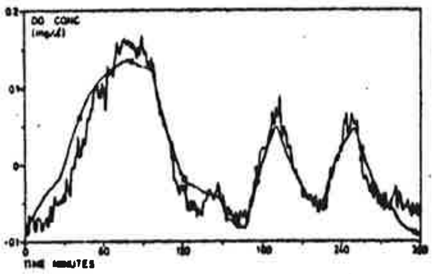

Fig. 2. DO output from the experiment in fig. 1. The real DO signal is compared with a first order model output.

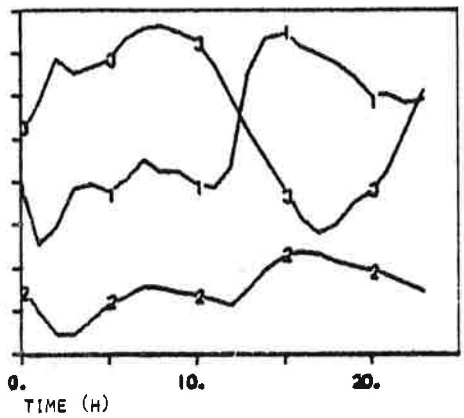

Fig. 4. DO control at Käppala. Hourly data of influent COD (1, mg/l), air flow rate (2, Nm^3/min) and influent flow rate (*100) (3, m^3/s)

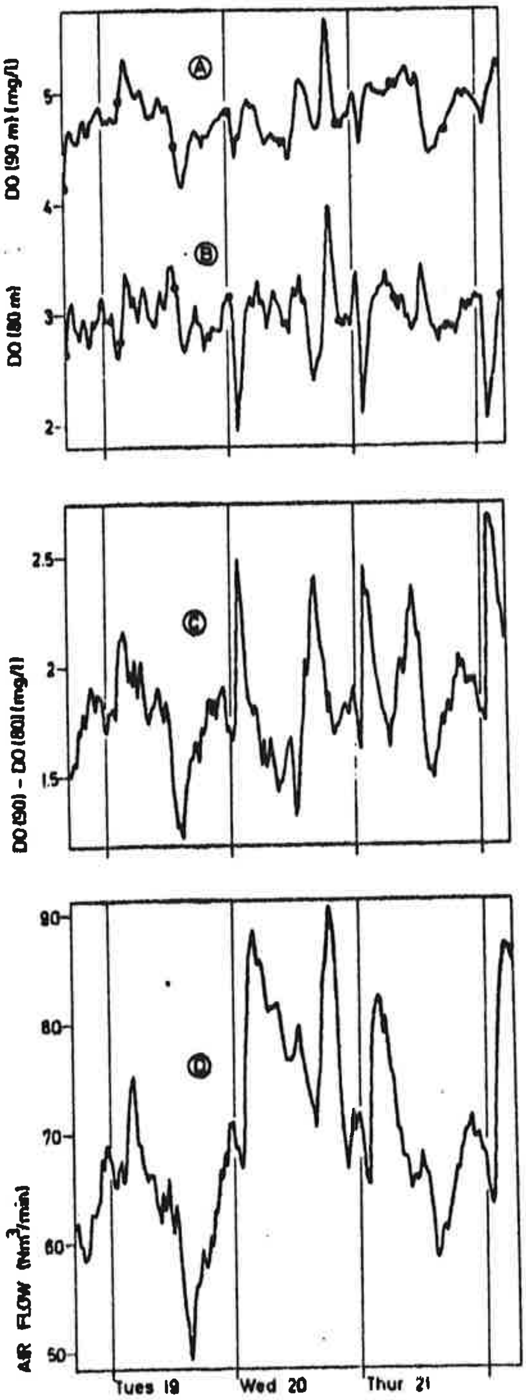

Fig. 3. DO control at the Käppala plant. The DO at position 80 m is controlled at 3 mg/l (B). The slope of the profile is defined as (C)=(A)-(B). C is strongly correlated to the air flow rate (D).

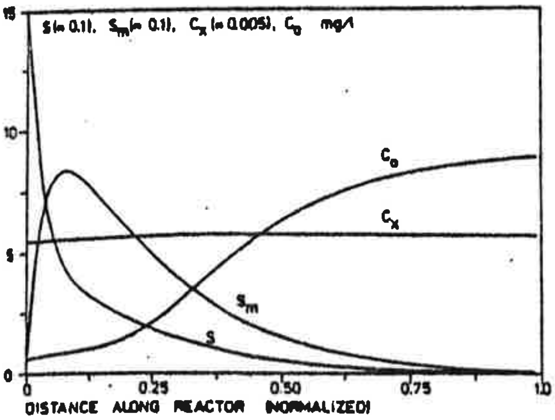

Fig. 5. Typical concentration profiles in a plug flow aerator with only organic removal. c_o=DO conc., c_x=living organism conc., s_m=stored mass, s=soluble mass.

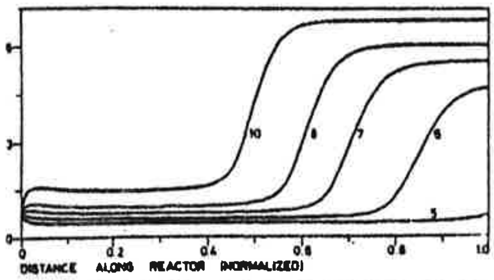

Fig. 6. DO profiles in a plug flow aerator with both organic removal and nitrification. The oxygen mass transfer coefficient (k_La) is parameter (hr^{-1}) as a measure of the air flow rate. k_La=5 corresponds to the air flow rate of fig. 5, where only organic removal occurs. Here k_La should be at least 7-8.

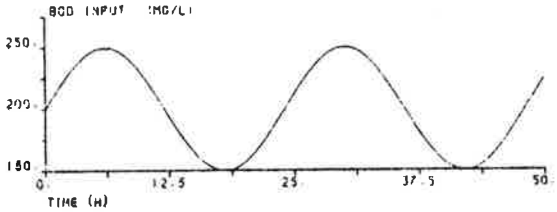

Fig. 7. The influent BOD disturbance.

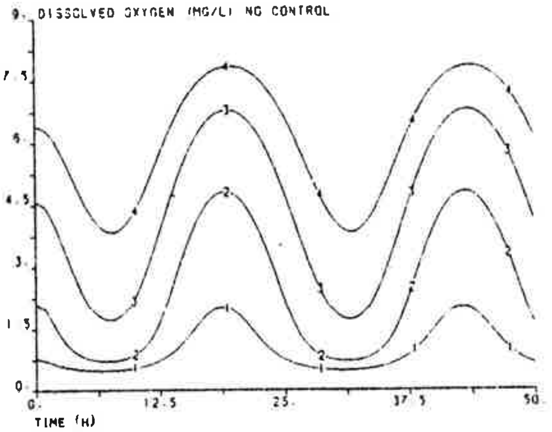

Fig. 8. Simulation of the activated sludge process with sinuoidal disturbances in flow rate and in influent BOD (fig 7). DO concentrations in the four subreactors. No DO control.

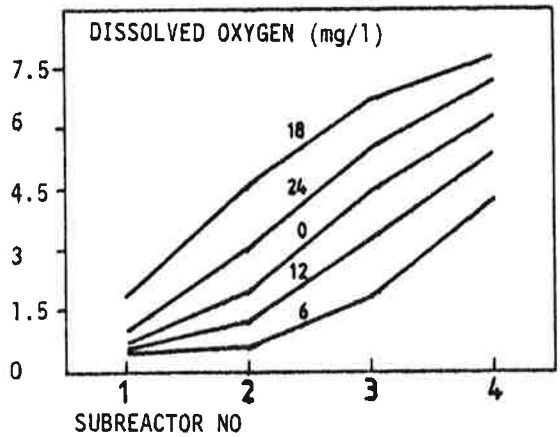

Fig. 9. The same simulation as in figs. 7 and 8. The same DO concentrations as in fig. 8, but here they are shown as function of space with time as a parameter.

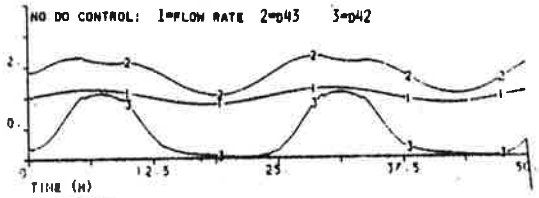

Fig. 10. The same simulation as in figs. 7-9. The influent flow variation (1) is shown together with the DO concentration slope d_{43} and the "second derivative" d_{42}. Cf. figs. 8 and 9.

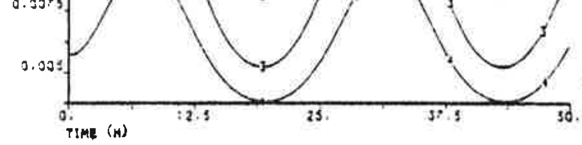

Fig. 11. The same simulation as in figs. 7-10. Specific oxygen utilization rates (SCOUR) in the four subreactors.

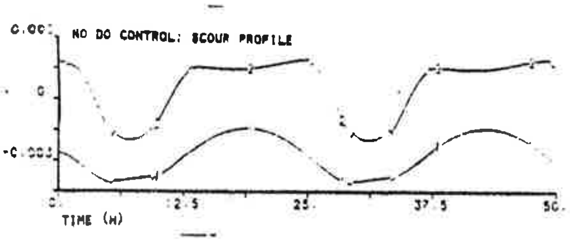

Fig. 12. The same simulation as in figs. 7-11. The slope SCOUR(4)-SCOUR(3) (curve 1) and the "second derivative" SCOUR(4)-2*SCOUR(3)+SCOUR(2) (curve 2). Cf. fig. 10.

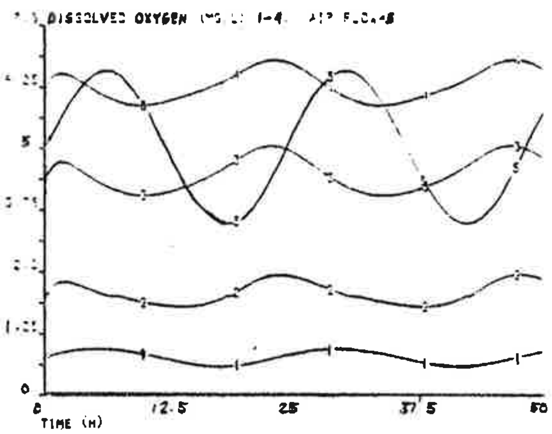

Fig. 13. Simulation of the controlled aerator. The disturbances are the same as in figs. 7-12. DO concentrations in the four subreactors. DO(3) is controlled. The air flow rate is also shown.

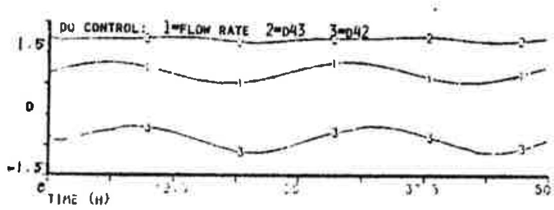

Fig. 14. The same simulation as in fig. 13. The slope of the DO concentration d_{43} is shown together with the "second derivative" d_{42} and the influent flow rate.