A CONTROL MODEL FOR ACTIVATED SLUDGE WASTEWATER TREATMENT PROCESS

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ABSTRACT

This paper discusses control of the conventional activated sludge process applied to biological wastewater treatment. Possibilities of process control by means of the sludge recycle and wasting flow rates are studied. The model developed includes a dynamic description of the final clarifier. The simulation results show that for each sludge age there exists a unique recycle and wasting flow rate pair which gives the maximal removal percentage. The diurnal variations decrease the removal percentage compared to the corresponding constant load case. A feedback-feedforward control system with a Luenberger type state observer for BOD is studied. It turns out that only little improvement can be gained by a system whose control variable is the recycle flow rate. The controller levels out the fluctuations of the sludge concentration. This decreases the hourly variations of the loading factor which may improve the performance more significantly in practice.

1. INTRODUCTION

The activated sludge process is commonly used in the biological treatment of waste waters, where the aim is to remove the dissolved organic material from the waste water. A simplified operating scheme of the process is presented in figure 1. The waste water is first fed to primary sedimentation, where the settleable solids are removed. The primary clarifier is followed by the aeration basin, where the clarifier effluent is contacted with aerobic micro-organisms (activated sludge). These consume the soluble organic material by converting it to metabolic products (mainly carbon dioxide and water) and to cell mass. The oxygen required by the micro-organisms is transferred to the water by powerful aeration of the basin contents, while simultaneous mixing is also achieved. From the aeration basin the mixture of sludge and water is fed to final clarification, where the sludge is separated by settling. Part of the sludge is pumped back to the aeration basin and part of it is removed from the process together with the solids from the primary clarifier for further treatment. The clarified water in the final sedimentation tank effluent is chlorinated before being discharged to the receiving water. Besides the biologically degradable organic material also inorganic nutrients such as nitrogen and phosphorus are removed to some extent, as these are needed as build-up material in cell production. The removal of nutrients can be increased by adding certain chemicals for precipitation. This can be done parallelly with the biological process (simultaneous precipitation). The amount of incoming waste to the treatment plant varies greatly during the day both in quality and quantity. Typically the influent flow rate may vary between values equal to 50 and 150 per cent of the mean flow rate and the concentration of the biologically degradable organic material respectively between 10 and 250 per cent when measured by its BOD-values (biological oxygen demand). Usually the peaks occur close to each other and thus the variations in the waste load are in fact significant. A typical diurnal load pattern of a medium size treatment plant is shown in figure 2. Besides the diurnal variations also other factors such as the weather conditions cause changes in the process loading. The diurnal pattern is usually quite regular and thus relatively well predictable. Until now only little interest has been taken in the control of the activated sludge process. The process has a certain inherent self-stabilizing property, which guarantees its functioning unless the process is overloaded. However, by using a suitable process control strategy the performance may be improved. The high cost of aeration may thus also be lowered. In practice, the available control variables are the rate of sludge recycle, rate of sludge withdrawal and the aeration power. The air blowing rate has an effect on the amount of oxygen in the aeration basin liquid. It is commonly assumed that when oxygen is kept above a certain critical level (1-2 mg/l) then it is not a growth limiting factor for the activated sludge. The purification process itself is controlled by the sludge recycle and wasting rates.

The dynamics of the biological treatment process is not only dependent on the purely hydraulic variables but also on the microbial growth kinetics in the aeration basin. Operationally the process can be divided into two independent parts, the primary sedimentation being one and the aeration basin together with the final clarifier the other. Since the influent flow rate cannot usually be controlled in practice, it is also impossible to influence the performance of the primary sedimentation. To the dissolved material the primary clarifier is only a kind of filter which somewhat smoothens the time-variations. Control of the process can be achieved by the unit composed of the aeration basin and final clarifier. It will be seen later on that they are functionally closely related to each other. Thus only this unit will be considered in the following.

Various works dealing with the dynamic models of the activated sludge process have been published recently. Among others the following papers by different authors can be mentioned: Andrews [1-3], Andrews and Lee[4], Brett et. al. [6], Fan et. al. [10-12], Erickson et. al. [14], Moser et. al. [18], Ott and Bogan [19], Ramanathan and Gaudy [21], Wells and Stepner [23] and Westberg [24-25]. Although some of these papers deal only with the aeration basin considering it as biological continuous flow stirred tankreactor (e.g. [2, 8, 11, 12]). However, usually a process with organism recycle is studied. Besides the basic model with a single completely mixed aeration chamber also multistage processes (e.g. [4, 10, 14]) and different hydraulic flow-patterns have been studied e.g. [10, 14]. The kinetics of the biological growth process is commonly assumed to obey the so called Monod-model [17] valid for homogenous populations (in practice the populations are quite heterogeneous). The dynamic models have been used to describe the effects of the detention time and different ways of recycling the sludge on the process output. A serious lack in the studies published so far has been the unsatisfactory modeling of the clarifier dynamics. It has usually been unrealistic because the models have been based on the static steady state clarification and thickening equations. The only really dynamic model formulated for sludge separation seems to be the detailed model of Bryant and Wilcox [7]. In the present study, as far as the process model is concemed, special attention has been given to the description of the final clarifier and the aim has been to further improve its dynamic model.

Also the control and regulation of activated sludge process has been studied by many authors. Control problems from the practical point of view have been treated e.g. by Bernard [5] and Jenkins and Garrison [16]. An extensive review of the subject as a whole is presented in an Environmental Protection Agencys report [13]. Wells and Stepner have presented an advanced study aiming at the realization of a control system for the aeration. Regulation of the growth of the activated sludge has been studied by e.g. Brett et. al. [6], D'Ans et. al. [8], Fan et. al. [11-12] and Westberg [24-25]. When the practical applicability of the proposed regulator constructions is considered certain unsatisfactory features arise. For example in a number of papers e.g. [8,11,12] the plant influent flow rate has been used as the control variable. Control of the influent flow is, however, seldom possible without a buffer storage basin, whose construction becomes troublesome and expensive. Moreover in all of these control models an on-line measurement of the BOD-value would be needed which at present is not generally possible to obtain. On-line instruments are still under development [15] and not yet commercially available.

The control system studied in this paper does not have these unrealistic features and can thus be better applied in practice. The controller uses an estimated BOD-value, which is obtained on the basis of the aeration basin sludge concentration (MLSS) and the flow rates. The control variables are the sludge recycle and wasting rates. Beside a feedback part, the control system consists of a feedforward part, with the aid of which the diurnal loading variations are directly compensated.

2. THE PROCESS MODEL

Figure 1 shows the process unit considered, consisting of the aeration basin and the final clarifier. Following nomenclature is used:

V	= aeration basin volume	$[m^3]$
F	= influent flow rate	$[m^3/h]$
F_R	= recycle flow rate	$[m^3/h]$
F_W	= excess sludge removal rate	$[m^3/h]$
X	= sludge concentration in the aeration basin (MLSS concentration)	$[g/l]$
X_R	= thickened sludge concentration at the bottom of the final clarifier	$[g/l]$
X_E	= sludge concentration in the final clarifier effluent	$[g/l]$
S_i	= influent flow BOD-concentration	$[mg/l]$
S	= aeration basin BOD-concentration	$[mg/l]$
S_E	= final clarifier effluent BOD concentration	$[mg/l]$

The aeration basin is treated as a completely mixed tank. This assumption is quite strongly idealized because the basin is more long than broad in its geometric form. A better result could be obtained by using some kind of a plug flow model with axial mixing (a series of completely mixed tanks or a dispersion model, see e.g. [10]). For process control studies, however, a simple model is probably sufficient. The growth of the sludge biomass is assumed to follow the so-called Monod-model [17] when the growth limiting nutrient is the biodegradable organic matter, measured by its oxygen demand equivalent (BOD). This model is again a simplification because it is valid only for homogeneous cultures of micro-organisms, and activated sludge is a very heterogeneous one. However, the Monod-model has been accepted as an approximative growth model. The effect of recycle sludge BOD can be neglected compared to the influent BOD load. By the above assumptions the biological growth dynamics in the aeration basin can be represented as follows:

$$\dot{S} = \frac{F}{V}\,[S_i - S] - \frac{1}{Y}\,\mu(S)X - \frac{F_R}{V}S, \qquad (1)$$

$$\dot{X} = \frac{F_R}{V}\,X_R + \mu(S)X - \frac{F + F_R}{V}\,X - k_D X, \qquad (2)$$

where

$$\mu(S) = \frac{\hat{\mu}\, S}{S + K_S} \qquad (3)$$

is the specific growth rate coefficient, Y is the so-called yield coefficient and k_D is a coefficient which corresponds to organism decay. The yield coefficient indicates the amount of biomass produced when one unit of substrate is metabolized, i.e. for differences the following equation is valid

$$\Delta X = - Y\Delta S. \qquad (4)$$

In the representation (3) $\hat{\mu}$ is the maximum value of the specific growth rate coefficient and K_S is the saturation coefficient equal to the substrate concentration, which gives the value $\hat{\mu}/2$ for μ. The dissolved oxygen balance equation has not been included in the model because oxygen control is not considered. The oxygen level is assumed high enough so that oxygen is not a growth limiting factor.

So far little research has been made on the dynamic models of final clarifiers. Most results concern the static properties. An example is the extensive study made by EPA [26]. After Pflanz [20] field experiments show that in a steady state the effluent sludge concentration can be approximately determined from the equation

$$\bar{X}_E = K \frac{F + F_R}{A} \bar{X}, \qquad (5)$$

where A is the surface area of the clarifier. The value of coefficient K varies from 8.10^{-2} to 10.10^{-2} $[\frac{h}{m}]$ (depending e.g. on the water temperature). Supposing this is valid, then the sludge concentration at the bottom of the clarifier can easily be calculated and is given by

$$\bar{X}_R = \frac{F + F_R}{F_R + F_W} \left(1 - K \frac{F - F_W}{A}\right)\bar{X} \qquad (6)$$

Because sludge does not concentrate to an infinite concentration this equation cannot be valid when $F_R + F_W \rightarrow 0$. In practice the maximum value is 10-18 g/l depending e.g. on the sludge volume index. When the maximum value is not exceeded the equation (6) can be expected to hold.

Some tracer studies have been made to find out the detention time distributions of solids and liquid in final clarifiers e.g. [22]. These experiments show that the sludge travels through the settling part almost as a bulk, being only slightly mixed and the dissolved matters go through the clarification part in the same way but being somewhat more mixed. As a first approximation the dynamics into both directions can thus be described by the aid of a time delay and a completely mixed tank. Figure 3 demonstrates this clarifier model. For simplicity it is assumed that sludge and dissolved matters (BOD) travel through the same dynamics. The clarifier equations then take the form

$$\dot{X}_E(t) = \frac{F(t) - F_W(t)}{V_E} \left(-X_E(t) + K\frac{(F(t-\Delta_E) + F_R(t-\Delta_E)}{A} X(t-\Delta_E)\right), \qquad (7)$$

$$\dot{S}_E(t) = \frac{F(t) - F_W(t)}{V_E}\left(-S_E(t) + S(t-\Delta_E)\right), \qquad (8)$$

$$\dot{X}_R(t) = \frac{F_R(t) + F_W(t)}{V_R}\left(-X_R(t) + \frac{F(t-\Delta_R)+F_R(t-\Delta_R)}{F_R(t-\Delta_R)+F_W(t-\Delta_R)}\left(1-K\frac{F(t-\Delta_R)-F_W(t-\Delta_R)}{A}\right)\cdot X(t-\Delta_R)\right), \qquad (9)$$

where

Δ_E = time delay in the clarification part,

Δ_R = time delay in the settling part,

V_E = mixing volume in the clarification part,

V_R = mixing volume in the settling part.

An estimate for the total sludge mass at the bottom of the clarifier can be obtained from the equation.

$$M = X_R V_R \qquad (10)$$

On the other hand the sludge blanket depth cannot be obtained from the present model. Likewise, changes in the settling properties of sludge are not considered. If these features should be considered a model like that of Bryant and Wilcox [7] may be used.

When determining the removal efficiency of the plant, the total BOD-concentration in the final clarifier effluent should be estimated by taking into account the BOD-equivalent of the effluent sludge. In this study the total BOD-concentration is defined as

$$S_{ET} = S_E + 0{,}6\, X_E. \qquad (11)$$

3. OPTIMIZATION AND CONTROL

A well designed control system of an activated sludge process should serve two objectives. First, it should maximize the treatment efficiency, and secondly, it should minimize the operating cost due to aeration energy and precipitation chemicals (if used). In this study we consider only the first objective, as aeration and precipitation are not included in our model. A control system which maximizes the treatment efficiency should maintain the process in a steady state, which gives the best removal percentage, in spite of load variations. It is well known that the most effective control variable would be the influent flow rate, if it could be used. As mentioned before, the use of the influent flow rate is in most cases impossible, because a large buffer storage is needed. Such a storage is expensive and also causes other problems. The control variables which normally can be applied are the sludge recycle and wasting rates.

There are two important variables which influence the treatment efficiency of an activated sludge process. These are the loading factor ($\triangleq$ LF) and the sludge age ($\triangleq$ SA) defined by

$$LF \triangleq \frac{\text{kg BOD removed/hours (or day)}}{\text{kg sludge in the aeration tank}}, \qquad (12)$$

$$SA \triangleq \frac{\text{kg sludge in the syste}}{\text{kg sludge wasted/day}} \qquad (13)$$

If most of the sludge in the system is in the aeration tank, it can be shown that the average (per day) values of LF and SA are related roughly by the equation [16]

$$\frac{1}{SA} = Y \cdot LF - k_D \qquad (14)$$

The control system should maintain a proper value of SA and compensate hourly variations in LF as much as possible. A constant sludge age also gives a constant average loading factor. The sludge settleability is strongly influenced by the loading factor so that its control is important. The direct control, however, involves the on-line measurement of the influent BOD, which is impossible in practice. The sludge age is much easier to control as only flow and suspended solids measurements are needed.

In the following simulation, studies are reported, which illustrate the possibilities for the control of an activated sludge process. The model is the one given before and numerical values are

$\hat{\mu}$ = 0,2 [1/h]

K_S = 200 [mg/l]

Y = 0,5 [mg/ml]

k_D = 0,005 [1/h]

V = 600 [m^3]

A = 50...400 [m^2]

K = $10 \cdot 10^{-2}$ [h/m]

V_E = 200 [m^3]

V_R = 100 [m^3]

Δ_E = 1,3 [h]

Δ_R = 1 [h]

The daily loading pattern was supposed to be of the form shown in figure 2. The pattern is the same as used by Bryant and Wilcox[7].

3.1 Operation under constant load

Operation under constant load was first studied. The values of the influent flow and BOD-concentration, $\bar{F}$ = 153 [m^3/h] and $\bar{S}_i$ = 215 [mg/l], were chosen so that $\bar{F} \cdot \bar{S}_i = \overline{FS_i}$, where $\overline{FS_i}$ is the mean value of the variable load. Figure 4 shows how the steady state values of the process variables depend on the sludge recycle and wasting rates. It can be seen that for a given sludge age there exists an optimal recycle flow rate. The removal percentage can be increased to a limit by increasing the sludge age. It should be noted, however, that as the model is not valid for large values of X_R then it's not valid for large values of the sludge age with small values of the recycle flow rate. Further, it is seen that a given sludge age can be obtained by several combinations of the recycle and wasting flow rates. These give, however, different values to the removal percentage and only one pair gives the optimal value. Thus, if a sludge age is chosen, it determines the recycle and wasting flow rates uniquely. Figure 4 further shows that the maximum removal percentage is quite sensitive to the clarifier surface area. When considering the removal percentage it should be borne in mind that small changes may indicate considerable changes in the effluent quality. For example, increasing the removal percentage from 86 % to 90 % means 29 % decrease in the effluent BOD quantity.

3.2 Operation under variable load

Typical process responses to the variable load are shown in Figure 5. If the diurnal mean values at steady state are determined and the same variables as in Figure 4 are plotted, the curves have in principle the same form. The numerical values are different and it turns out that the treatment efficiency deteriorates somewhat. The following table illustrates typical differences between corresponding steady states with the constant and variable loads. In the case of the variable load the values are mean values over a full period.

F_R [m^3/h]	S_{ET} [mg/l]		sludge age [d]		removal percentage	
	constant	variable	constant	variable	constant	variable
40	27,0	31,5	6,1	5,8	87,7	85,5
50	26,6	30,3	6,4	6,2	88	86
60	26,6	29,9	6,6	6,6	88	86
70	26,9	29,7	6,8	6,7	87,7	86,5
80	27,3	29,8	6,9	6,9	87,5	86,5
90	27,7	30,0	7,0	6,8	87,5	86

F_W = 1,25 m^3/h, A = 200 m^2

The avarage difference between removal percentages is 2 units, which means 10-15 % difference in the effluent BOD. This difference seems to be the greatest possible profit that can be attained by means of a control system which levels out the effects of a variable loading. This is not very much, on the other hand the model does not consider the smoothing effect on the sludge settling properties. In practice, more profit may be attained by improved sludge settleability.

3.3 The control system

The control system considered is outlined in figure 6. The system includes feedback and feedforward parts. Both effect the recycle flow rate F_R. The feedback part compensates variations of the quantities X, X_R and S from their set point values, which are chosen according to the desired steady state values. The feedforward part assists the feedback part by anticipating the diurnal variations in the influent flow rate. Control of the sludge mass in the system is done by a separate controller which acts on the sludge wasting rate. The sludge removal is done in such a way that a planned sludge age is maintained.

The feedback-feedforward controller is designed by using the standard linear-quadratic techniques. The design is based on a linear discrete time model of the process, which makes it possible to apply digital realization techniques. The model used is of the form

$$y(i+1) = Ay(i) + Bu(i) + Ew(i), \quad (15)$$

where

$$y(i) = \begin{bmatrix} \Delta x(i) \\ \Delta x_R(i) \\ \Delta S(i) \end{bmatrix}, \ u(i) = \Delta F_R(i), w(i) = \Delta F(i).$$

The Δ-quantities correspond to the variations from the set point values. The control law obtained is of the form

$$\Delta F_R(i) = Gy(i) + Z(i), \quad (16)$$

where $G = [g_1 g_2 g_3]$ is a constant feedback matrix and Z(.) a periodic feedforward function which predicts the diurnal variations in the influent flow rate F. Supposing the standard quadratic criterion

$$J = \frac{1}{2} \sum_{i=0}^{k} [x(i)^T Qx(i) + u(i)^T Ru(i)] \quad (17)$$

with positive definite weighting matrices Q and R , the feedback matrix G is obtained from the equation

$$G = R^{-1}B^T A^{T^{-1}} (K + Q), \quad (18)$$

where K is the steady state solution of the Riccati difference equation

$$K(i) = A^T K(i+1)(I - BR^{-1}K(i+1))^{-1}A - Q, \quad (19)$$

$$K(k) = 0$$

The control interval [0,k] is supposed to be sufficiently large. The feedforward function Z(.) is obtained from the equation

$$Z(i)-Z(i+1) = (K(i)+Q)A^{-1}(BR^{-1}B^T Z(i+1)+Ew(i)), \quad (20)$$

$$Z(k) = 0.$$

When applying the control law, $y_3(i) = \Delta S(i)$ is substituted by an estimated value $\Delta\hat{S}(i) = \hat{S}(i) - \bar{S}$ given by the following estimator (Luenberger-type state observer)

$$\dot{\hat{S}} = \frac{F}{V}(\bar{S}_i - \hat{S}) - \frac{1}{Y}\mu(\hat{S})X - \frac{F_R}{V}\hat{S}, \quad (21)$$

which operates with measured values of X, F and F_R ($\bar{S}_i$ is the mean value of S_i).

Adjustment of the control system is done by first finding an optimal steady state which corresponds to a preselected sludge age. The sludge wasting rate is controlled so that this age is maintained. The adjustment of the feedback - feedforward part is then done by experimenting with different weighting matrices in the performance index (17). Improvements in the treatment efficiency and smoothing of fluctuations can be used as a criterion.

In the simulation studies the model (15) was identified separately from the simulation process (analog simulation) by a technique based on regression analysis. The technique has no general interest and is not described more closely here. The discretization interval used was $\frac{1}{2}$ hours. The best controller was obtained by weighting relatively strongly the estimated value of S. However, there were no considerable differences between different adjustments. A pure F_R/F - ratio control was also studied and it was found nearly as good as the feedback-feedforward controllers. The improvement in the treatment efficiency was in the best case only one unit in the removal percentage, which means 5-10 % decrease in the effluent BOD. Typically, for example, if the sludge age is 6,7 days, the optimal constant values of the recycle and wasting flow rates are $F_R = 70\ m^3/h$ and $F_W = 1{,}25\ m^3/h$. Under the constant load the effluent total BOD is 98 kg/day, under the variable load the corresponding value is 116 kg/day, and when a feedback - feedforward or ratio controller is used it is 111 kg/day. The smoothing effect of the controllers is, however, quite considerable as can be seen in Figure 5 (dotted lines). Figure 5 also shows how the controllers change the recycle flow rate and how the estimated value of S behaves. The loading factor varies hourly in the uncontrolled case from $4{,}3 \cdot 10^{-3}$ to $8{,}4 \cdot 10^{-2}$ kg/kg · h and in the controlled case from $5{,}1 \cdot 10^{-3}$ to $7{,}1 \cdot 10^{-2}$ kg/kg · h. The daily avarage value is in both cases ~ $7{,}2 \cdot 10^{-1}$ kg/kg · d (if compared with normal practice the process is slightly overloaded).

A conclusion from the simulation results is that the compensation of the diurnal variations by means of the recycle flow rate is not quite effective. This is mainly due to the fact that although increasing the recycle flow rate decreases the BOD-concentration in the aeration basin, it increases at the same time solids flux to the final clarifier. The sludge solids escaping to the clarifier effluent thus also increase causing the corresponding BOD load to increase. It seems also that the diurnal variations are too fast for the biological process. Especially this concerns the variations of the influent flow rate. If the influent is constant the process smoothens the variations in the influent BOD concentration much better. Slower fluctuations such as day-to-day variations can be more easily compensated.

4. SUMMARY AND CONCLUSIONS

In the paper the conventional activated sludge process applied to biological wastewater treatment is considered. Recently, there has been increasing interest in this process because of increasing automation of wastewater treatment plants. The activated sludge process is the main unit process of a biological treatment plant and is applied especially to reduce the BOD content of the waste water. The amount of incoming waste to the treatment plant normally varies greatly both in quality and quantity. There exists a clearly detectable diurnal rhythm and besides this also other fluctuations. Due to the variations process control is needed to maintain the treatment efficiency as high as possible. The paper studies the possibilities of process control by means of the sludge recycle and wasting flow rates. The considerations are based on a quite simple model, which includes only the mass balance equations for the activated sludge and the waste water BOD. The model does not take into account many important variables and effects in the process, but it can be regarded valid if only BOD removal is considered. The model describes only the viable part of the activated sludge, because the mass balances of waste water suspended solids and dead cells are not included. Special attention has been paid to the role of the final clarifier in the process. In most previous studies the final clarifier has been described only qualitatively.

The simulation results show that the sludge recycle and wasting flow rates have a considerable effect on the treatment efficiency in a steady state operation. The maximum removal percentage that can be attained depends mainly on the mean sludge retention time or the sludge age in the process. At each sludge age there exist a unique recycle flow rate and wasting flow rate pair which give the maximum removal percentage at this age. The simulation results further show that diurnal variations decrease the removal percentage if compared with corresponding constant load. However there seems to exist only little possibilities to compensate this effect by using a system whose control variable is the recycle flow rate. Both feedback and feedforward control actions were studied. This is mainly due to the fact that although increased recycle flow rate decreases BOD concentration in the aeration basin, it at the same time increases solids flux to the final clarifier causing more sludge to escape to the process effluent. By taking into account the BOD content of the sludge solids the increased recycle flow rate may increase the total effluent BOD. The results are in this respect similar to those obtained by Bryant and Wilcox[7] before. On the other hand, the control system levels out the fluctuations of the sludge concentration in the aeration basin quite effectively and thus it also decreases the hourly variations of the loading factor. The model does not consider the effect of the loading factor to sludge settleability. It is well known that such an effect may be considerable and it can be supposed therefore, that the compensation of the diurnal variations may improve the removal percentage more in practice.

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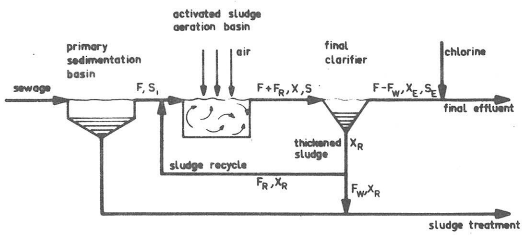


Figure 1. The conventional activated sludge process

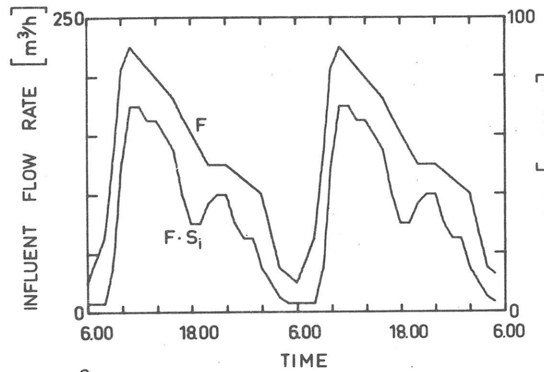


Figure 2a.

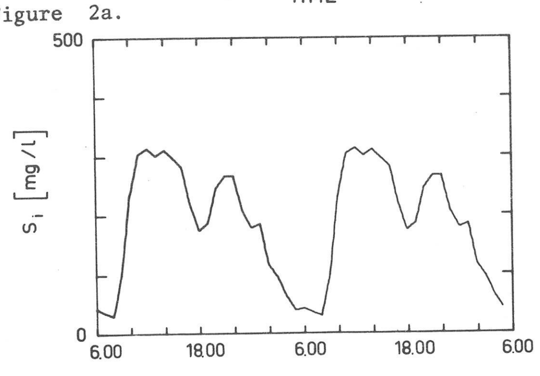


Figure 2. A typical diurnal load pattern of a medium size treatment plant.

a) Influent flow and BOD load fluctuations.

b) Fluctuations in BOD concentration.

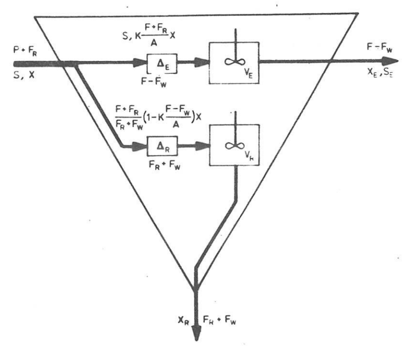
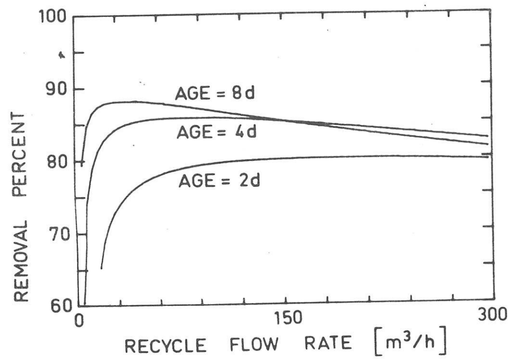


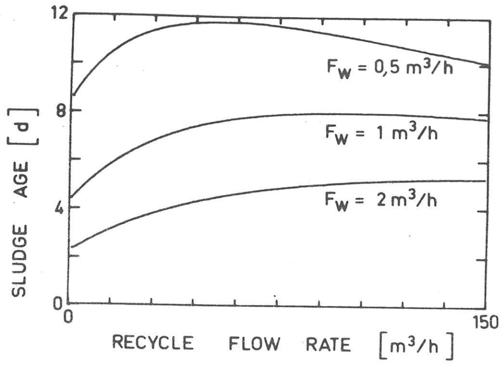
Figure 3. A model of the final clarifier.

Figure 4. Steady state values of the activated sludge process model with a constant load (33 kg BOD/h).



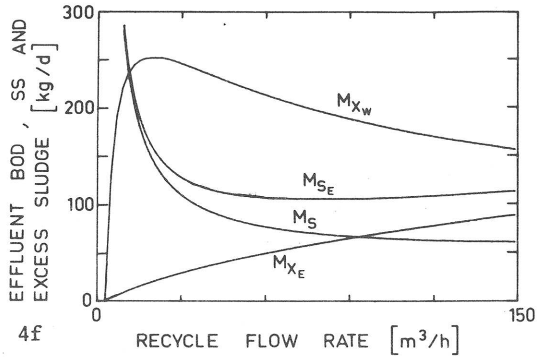
4a

a) Removal percentage as a function of the recycle flow rate when the sludge age is constant ($A = 200\ m^2$).



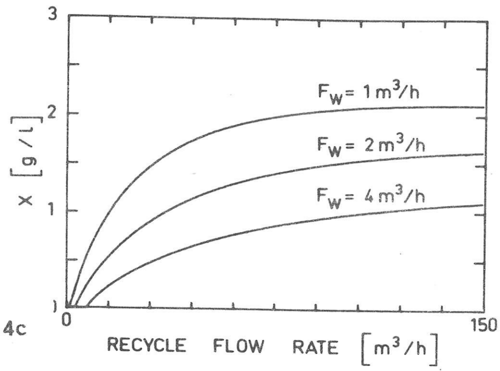
4b

b) The sludge age as a function of the recycle flow and wasting flow rates (A = 200 m^2).

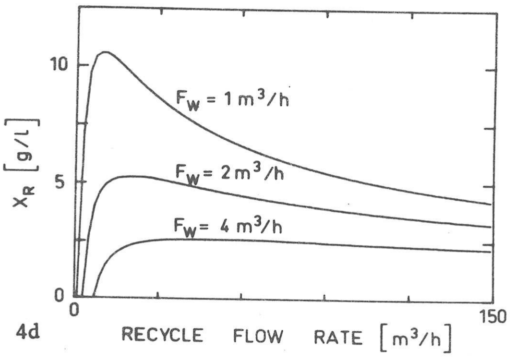


4f

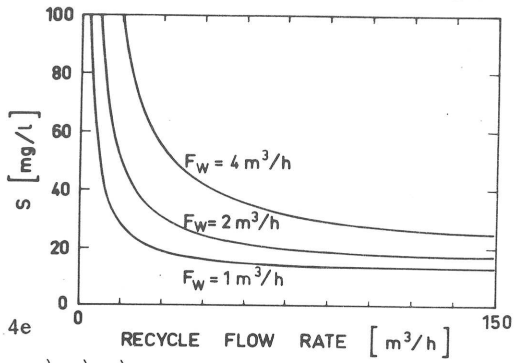
f) Effluent BOD (M_{SE}), sludge solids (M_{XE}) and wasted sludge (M_{XW}) as a function of the recycle flow rate when the wasting flow rate is constant (F_W = 2 m^3/h, A = 200 m^2).



4c

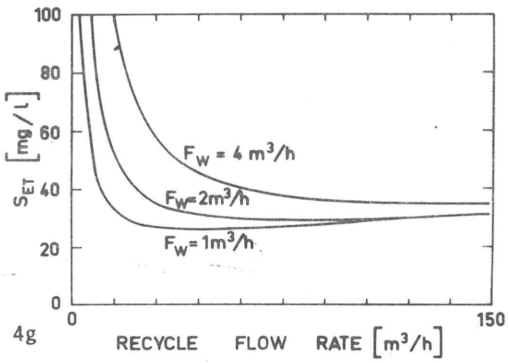


4d



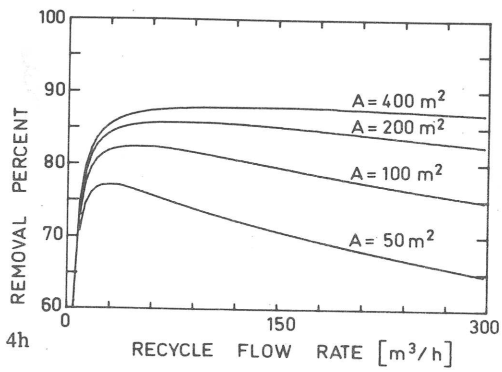
4e

c),d),e) The aeration basin sludge concentration, the recycle flow sludge concentration and the aeration basin BOD concentration as a function of the recycle flow and wasting flow rates (A = 200 m^2).



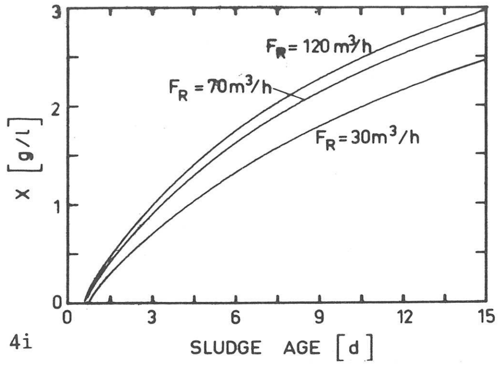
4g

g) Effluent BOD concentration as a function of the recycle flow and wasting flow rates.



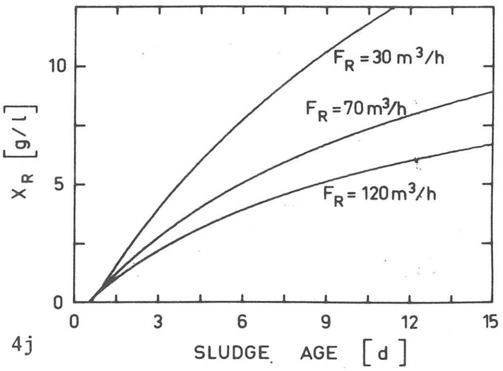
4h

h) Removal percentage as a function of the final clarifier surface area and the recycle flow rate (sludge age = 4 days).



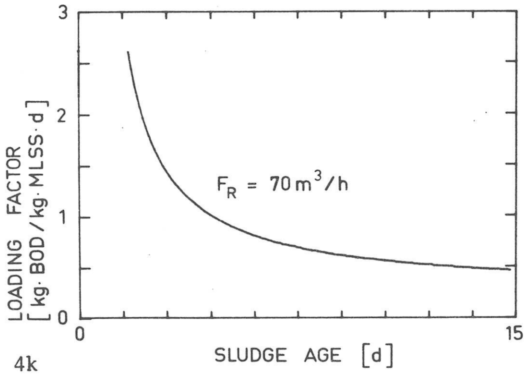
4i

i) The aeration basin sludge concentration as a function of the sludge age and the recycle flow rate ($A = 200\ m^2$).



4j

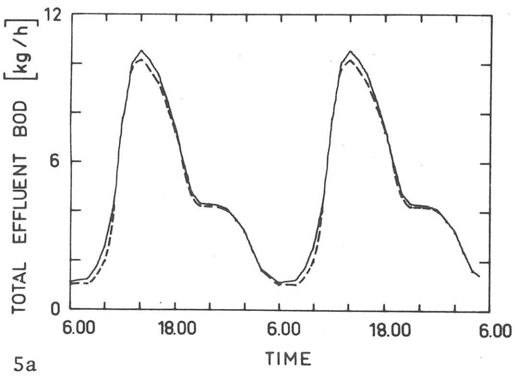
j) The recycle sludge concentration as a function of the sludge age and the recycle flow rate ($A = 200\ m^2$).



4k

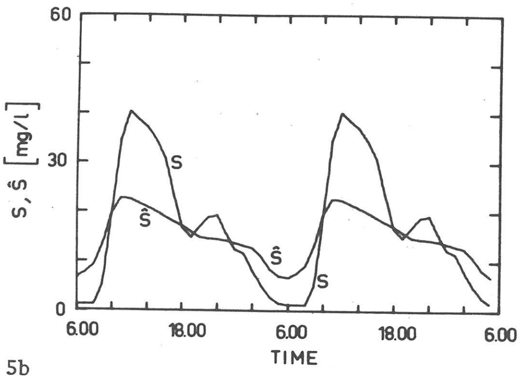
k) The loading factor as a function of the sludge age when the recycle flow rate is constant ($F_R = 70\ m^3/h$, $A = 200\ m^2$).

Figure 5. Time responses of the activated sludge process model. The sludge age is 6,7 days. Solid lines represent the situation when no control is applied (constant recycle flow rate) and dotted lines the situation when the feedback - feedforward control (---) and the proportional control (-·-·-) are applied.



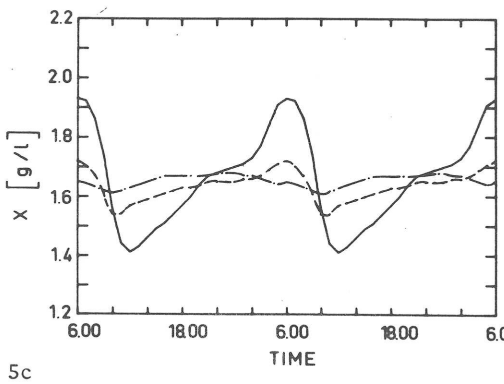
5a

a) Total effluent BOD.



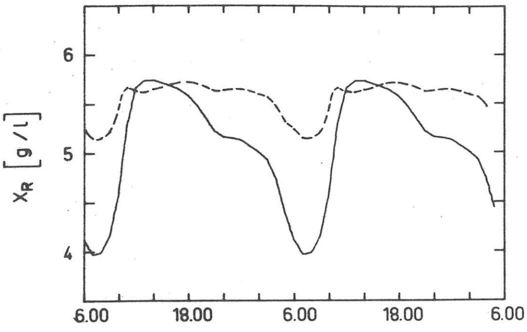
5b

b) The aeration basin BOD concentration and its estimated value Ŝ.



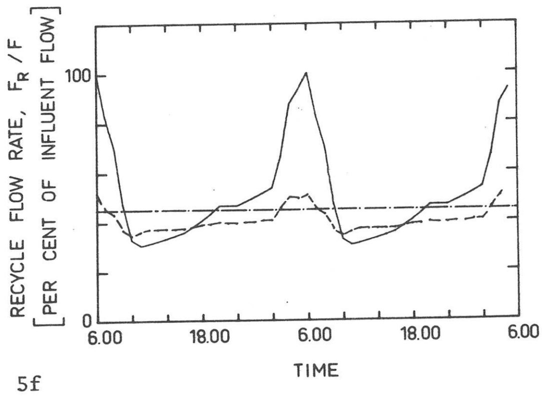
5c

c) The aeration basin sludge concentration.



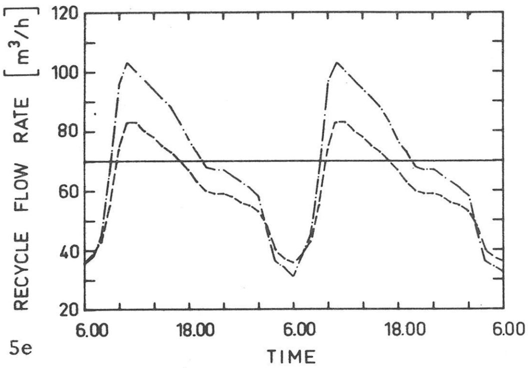
5d

d) The recycle flow sludge concentration.



5f

f) The recycle flow rate percent of the influent flow rate.



5e

e) The recycle flow rate.

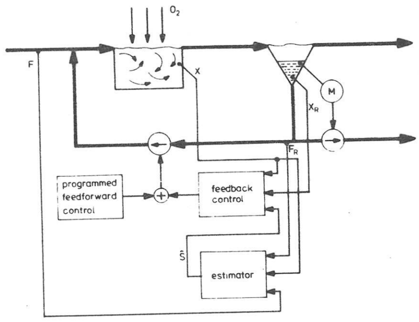


Figure 6. The control system considered in the text.