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# BIOLOGICAL TREATMENT OF INHIBITORY SUBSTRATES

Some types of industrial wastewaters involves specific problems when treated in biological processes. They are due to the presence of biodegradable inhibitory substrates which can affect microbial growth, especially when occurring in high concentrations. The treatment of such wastewaters in an activated sludge process in a continuously fed stirred tank reactor has a marked disadvantage which lies in the fact that the work of the tank may become unstable in a certain range of retention times. The efficiency of the process may substantially change even at small variations of the process parameters. In the study reported the unstability was related to the initial concentrations of pollutants, to some parameters of the process and to the parameters of microbial kinetics. Theoretical considerations show that for a certain range of pollutant concentrations in a raw wastewater the unstable work of the reactor can be eliminated.

The methods analyzed in this paper were as follows: intensive recirculation of the effluent from the secondary settling tank, supply of biomass (from outside of the system) to the incoming wastewater, dilution of the influent with water or sewage containing no inhibitory substrates, and immobilization of the biomass on the carrier in the activated sludge tank. Of the methods tested, immobilization of the biomass was found to be the most efficient.

## NOTATIONS

$c$ – dimensionless maintenance coefficient,
$D$ – dilution rate, $T^{-1}$,
$k$ – dimensionless inhibition coefficient,
$K_I$ – inhibition constant, $ML^{-3}$,
$K_S$ – Michaelis–Menten constant, $ML^{-3}$,
$m$ – maintenance coefficient, $MM_x^{-1}T^{-1}$,
$Q_1$ – influent flow rate, $L^3T^{-1}$,
$Q_5$ – return sludge flow rate, $L^3T^{-1}$,
$S_1$ – influent substrate concentration, $ML^{-3}$,
$\tilde{S}_1$ – dimensionless influent substrate concentration,
$S_2$ – effluent substrate concentration, $ML^{-3}$,

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$\tilde{S}_2$ – dimensionless effluent substrate concentration,
$t$ – chronological time, $T$,
$\tilde{t}$ – dimensionless chronological time,
$V_2$ – void space of reactor, $L^3$,
$X_1$ – influent biomass concentration, $M_x L^{-3}$,
$X_2$ – mixed liquor suspended solids, $M_x L^{-3}$,
$X_3$ – biomass concentration in effluent from secondary settling tank, $M_x L^{-3}$,
$X_5$ – concentration of recirculated biomass, $M_x L^{-3}$,
$X_{5,Q}$ – "reduced" concentration of recirculated biomass, $X_{5,Q} = \alpha X_5$, $M_x L^{-3}$,
$\tilde{X}_{5,Q}$ – dimensionless form of $X_{5,Q}$,
$X_A$ – concentration of immobilized biomass, $M_x L^{-3}$,
$\tilde{X}_A$ – dimensionless concentration of immobilized biomass,
$X_D$ $= X_A + \dfrac{X_1 + X_{5,Q}}{1+\alpha}$, $M_x L^{-3}$,
$\tilde{X}_D$ – dimensionless form of $X_D$,
$Y$ – biomass yield coefficient, $M_x M^{-1}$,
$Y_{obs}$ – net biomass yield coefficient, $M_x M^{-1}$,
$\alpha$ – recirculation ratio ($\alpha = Q_5/Q_1$),
$\beta$ – degree of excess sludge removal ($\beta = Q_4/Q_1$),
$\Theta$ – space time (HRT), $T$,
$\tilde{\Theta}$ – dimensionless space time,
$\mu$ – specific biomass growth rate, $T^{-1}$,
$\mu_{max}$ – maximum specific biomass growth rate, $T^{-1}$.

## 1. INTRODUCTION

The objective of the study was to analyze a number of problems approached in the activated sludge treatment of a specific type of industrial wastewater conducted in a tank with complete mix.

Of the formulae available for describing the kinetics of biological treatment, Monod's empirical equation [12]

$$\mu = \frac{\mu_{max} S_2}{K_s + S_2}$$

is usually regarded as best suited for this purpose. Monod's formula expresses the relationship between the microbial growth rate $\mu$ and growth-limiting substrate concentration $S_2$. When the wastewater to be treated contains many different substrates (which is rather typical of industrial wastes), substrate concentration will be expressed in terms of dichromate COD, $C_{org}$ or BOD. The plot for Monod's equation is shown in fig. 1. If this equation holds, it should be noted that each value of $\mu$ will have only one correspondent value of $S_2$.

However, in some instances Monod's formula is no longer sufficient to describe the degradation of substrate contained in the wastewater. This is, for example, true for phenols [4], [10], [11], [13], [14], n-butanol [18], pentane [17], phenyl acetate, sodium benzoate, p-sodium hydroxybenzene [9], nitrites [1], especially when occurring over a wide range of concentrations. For these substrates other empirical formulae (as that given in fig. 2) should be derived to describe the $\mu - S_2$ relationship. EDWARDS [6] gave a detailed account of the mechanisms governing the inhibition of microorganisms growth by high substrate concentrations. The problem of inhibition has been intensively studied and a great number of useful results published. The literature contains different expressions and formulae to describe the relationship of interest [6], [19], [20]. The following equation known as Monod–Haldane model is most frequently used:

$$\mu = \frac{\mu_{\max} S_2}{K_S + S_2 + S_2^2/K_I}.$$

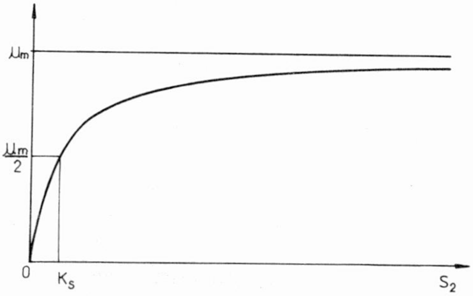


Fig. 1. $\mu$ versus $S_2$ curve (according to MONOD [12])

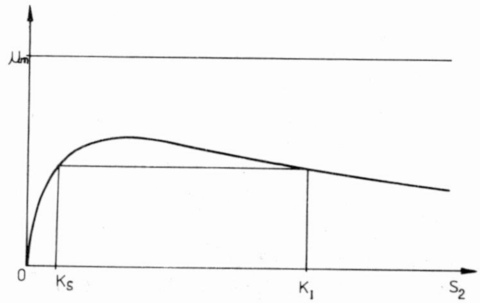


Fig. 2. $\mu$ versus $S_2$ curve (according to EDWARDS [6])

This model will also be included in our considerations. Irrespective of whether or not our considerations involve Haldane's model, it should be noted here that in every $\mu$ versus $S_2$ relationship similar to the one shown in fig. 2 (i.e., each value of $\mu$ has two corresponding values of $S_2$), our conclusions qualitatively hold.

## 2. DETERMINING THE $\mu$ VERSUS $S_2$ RELATIONSHIP

Considering the treatment of specific wastewaters in an activated sludge process, it should be determined whether the nature of the relationship in question is that of fig. 1 or that of fig. 2. If the wastewater to be treated contain the specific substances mentioned in the introductory comments, it can be expected that the $\mu - S_2$ relationship will be that of fig. 2.

The utilization of continuous or batch cultures is one of the most frequently employed methods in determining the value of $\mu$. The advantages and limitations of the methods employed have been described in the literature a number of times [2], [3], [7], [8], [10], [13].

## 3. GENERALIZED MATHEMATICAL MODEL FOR WASTEWATER TREATMENT IN A CONTINUOUSLY FED STIRRED TANK REACTOR (CFSTR)

CFSTR is shown in fig. 3. It has been assumed that some part of the microorganisms can be immobilized on the carrier and that biomass may also be present in the feed.

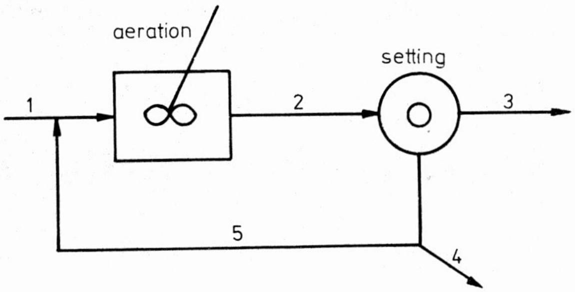


Fig. 3. CRSTR with recirculation

Under conditions similar to those of the steady state, the quantity of the biomass that can be recirculated is constant and can be determined from the balance of the biomass contained in the effluent from the CFSTR, the biomass removed as excess sludge and the biomass leaving the settling tank along with the treated wastewater. This balance can be written as follows:

$$Q_1 \alpha X_5 = Q_1 (1+\alpha) X_2 - Q_1 \beta X_5 - Q_1 (1-\beta) X_3 \tag{1}$$

$$\left\{\begin{matrix}\text{Biomass to be}\\ \text{recirculated}\end{matrix}\right\} = \left\{\begin{matrix}\text{Biomas leaving the}\\ \text{CFSTR}\end{matrix}\right\} - \left\{\begin{matrix}\text{Biomass contained}\\ \text{in excess slude}\end{matrix}\right\} - \left\{\begin{matrix}\text{Biomass in the effuent}\\ \text{from settling tank}\end{matrix}\right\}$$

Since under nearly steady-state conditions all of the terms on the right-hand side of eq. (1) can be considered constant, we may expect that $\alpha X_5 = X_{5,Q} = \text{const.}$ This means that at a given concentration of suspended biomass $X_2$ an increase in the recirculation ratio $\alpha$ will bring about a decrease in concentration of the recirculated biomass $X_5$. If there exists a possibility of increasing the concentration of recirculated biomass, the required recirculation ratio may be decreased.

Assuming that: 1) the CFSTR is able to ensure a complete mix, 2) the effective volume of the CFSTR is constant, and 3) the microorganisms immobilized on the carrier and living out of it as well as the microoorganisms coming from recirculation and those entering the reactor with the inflowing raw wastewater are identical, the biomass balance will take the form:

$$\frac{dX_2}{dt} = D[X_{5,Q}+X_1-(1+\alpha)X_2]+\mu(X_A+X_2). \tag{2}$$

If $X_1 = 0$, the model obtained will refer to a system with no biomass in the incoming raw wastewater. When $X_A = 0$, the model is valid for a system with no microorganisms immobilized on the carrier. Under steady-state conditions ($dX_2/dt = 0$)

$$\mu = \frac{D[(1+\alpha)X_2-X_1-X_{5,Q}]}{X_A+X_2}. \tag{3}$$

The equation of the substrate balance can be expressed as:

$$\frac{dS_2}{dt} = D(S_1-S_2)-\frac{\mu}{Y_{obs}}(X_A+X_2). \tag{4}$$

Under steady-state conditions ($dS_2/dt = 0$)

$$X_2 = \frac{Y_{obs}D(S_1-S_2)}{\mu}-X_A. \tag{5}$$

Comparing eq. (3) and eq. (5) gives

$$X_2 = \frac{Y_{obs}(S_1-S_2)+X_1+X_{5,Q}}{1+\alpha}. \tag{6}$$

Substituting $X_2$ from eq. (6) into eq. (4) and regarding

$$X_D = \frac{X_1+X_{5,Q}}{1+\alpha}+X_A$$

we obtain

$$\frac{dS_2}{dt} = D(S_1-S_2)-\mu\left(\frac{S_1-S_2}{1+\alpha}+\frac{X_D}{Y_{obs}}\right). \tag{7}$$

Introducing

$$\frac{1}{Y_{obs}} = \frac{1}{Y}+\frac{m}{\mu}, \qquad \mu = \frac{\mu_{\max}\cdot S_2}{K_S+S_2+\dfrac{S_2^2}{K_I}}, \qquad \mu_{\max}t = \tilde{t},$$

$$\mu_{\max}\Theta = \frac{\mu_{\max}}{D} = \tilde{\Theta}, \quad S_1/K_S = \tilde{S}_1, \quad S_2/K_S = \tilde{S}_2, \quad K_S/K_I = k,$$

$$\frac{X_D}{YK_S} = \tilde{X}_D, \quad \frac{X_A}{YK_S} = \tilde{X}_A, \quad \frac{X_1}{YK_S} = \tilde{X}_1, \quad \frac{X_{5,Q}}{YK_S} = \tilde{X}_{5,Q},$$

and

$$\frac{mY}{\mu_{\max}} = c$$

will give the dimensionless form of eq. (7):

$$\frac{d\tilde{S}_2}{d\tilde{t}} = \frac{1}{\tilde{\Theta}}(\tilde{S}_1 - \tilde{S}_2) - \frac{\tilde{S}_2\left(\tilde{X}_D + \dfrac{\tilde{S}_1 - \tilde{S}_2}{1+\alpha}\right)}{1 + \tilde{S}_2 + k\tilde{S}_2^2} + c\tilde{X}_D. \tag{8}$$

For steady-state conditions ($d\tilde{S}_2/d\tilde{t} = 0$) the equation reads:

$$\tilde{\Theta} = \frac{\tilde{S}_1 - \tilde{S}_2}{\dfrac{\tilde{S}_2\left(\tilde{X}_D + \dfrac{\tilde{S}_1 - \tilde{S}_2}{1+\alpha}\right)}{1 + \tilde{S}_2 + k\tilde{S}_2^2} + c\tilde{X}_D}. \tag{9}$$

## 4. RELATIONSHIP BETWEEN SUBSTRATE CONCENTRATION AND HYDRAULIC RETENTION TIME (HRT)

Figure 4 gives the curves of substrate concentration $\tilde{S}_2$ versus retention time $\tilde{\Theta}$ plotted for steady-state conditions according to eq. 9. The shapes of the $\tilde{S}_2$ versus $\tilde{\Theta}$ plots may be either those of fig. 4a or those of fig. 4b, depending on the values of the parameters $\tilde{S}_1$, $k$, $c$, $\tilde{X}_D$, and $\alpha$. When the curves have a shape as that of the

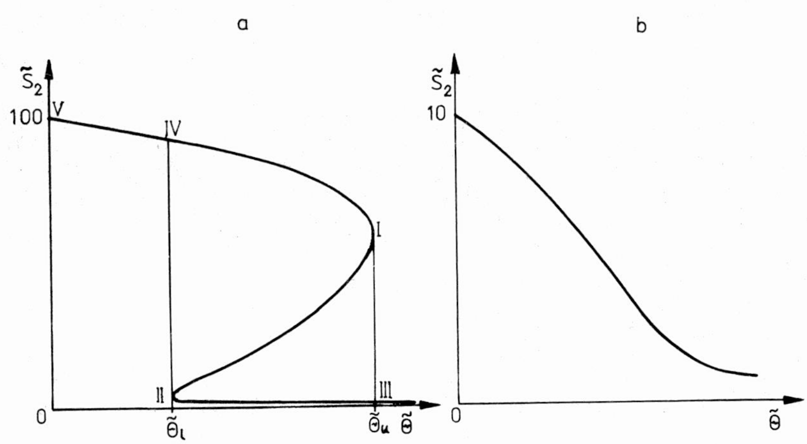


Fig. 4. $S_2$ versus $\Theta$ curves for steady-state conditions

$c = 0.2$, $k = 0.1$, $\alpha = 0.5$, $\tilde{X}_D = 10$, a) $\tilde{S}_1 = 100$, b) $\tilde{S}_1 = 10$

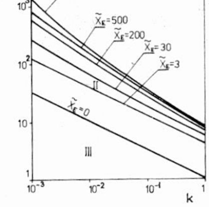


Fig. 5. Intervals in which multiplicity of steady states occurs

$c = 0.06$

fig. 4a plots, for the retention times ranging within $\tilde{\Theta}_l$ and $\tilde{\Theta}_u$, eq. (9) has three solutions. We can prove that the solutions contained in segment I–II of the curves are of an unstable nature [5], [15]. This means that the concentrations related to this segment do not occur in engineering practice, because once the concentration of the substrate in the reactor begins to increase (at least for a moment if not more), it continues to rise until steady-state conditions are reached such that correspond to the segment I–IV of the curve. If there is an instantaneous drop in the concentration of the substrate, the steady-state conditions in the reactor will be those included in segment II–III.

The operation of the CFSTR under steady-state conditions with decreasing times of retention from a value of above $\tilde{\Theta}_u$ to the level of $\tilde{\Theta}_l$ (i.e., in the range where multiplicity of steady-state conditions occurs) brings about a continual increase of substrate concentration in the reactor until point II has been reached. The further decrease of the retention time will lead to the "skip" to point IV, thus contributing to a rapid decrease in the efficiency of the CFSTR. If the retention time continues to decrease, the concentration of the substrate will continue to increase to reach the value of $S_1$ at point *V*. When the influent substrate concentrations ($\tilde{S}_1$) are high, the skip from point II to point IV (along with the resulting rapid increase in the concentration of the substrate inhibiting microbial growth) may cause the kill of the biomass, inhibition of its settleability and, consequently, a failure of the treatment process [16]. On the contrary, when starting from point V, the extension of the retention time brings about a continuous decrease of the substrate concentration until point I is reached. The further increase in retention time leads to a skip to point III to give a rapid improvement of the reactor efficiency.

In engineering practice it is difficult to provide steady-state conditions in the CFSTR because of the variability both in the rate of wastewater inflow and in the concentration of the substrates present there. The variable composition of the wastewater to be treated, which accounts for the variability of the parameters describing the kinetics of biodegradation, is also of great significance. Temperature seems to have a consistent effect and so does the microbial composition of the sludge. Consequently, the substrate concentration in the CFSTR only approaches the values of steady-state conditions. In the range of retention times between $\tilde{\Theta}_l$ and $\tilde{\Theta}_u$ it may happen, therefore, that instantaneous increment in the substrate concentration (reaching values higher than those included in segment I–II) will occur, thus contributing to a considerable decrease in the efficiency of the reactor or to a failure of the treatment process. There may also occur such a situation that the retention time $\tilde{\Theta}$ slightly exceeds $\tilde{\Theta}_l$, but an instantaneous increase in the rate of wastewater inflow will shorten the retention time to value below $\tilde{\Theta}_l$ and bring about a skip to very high concentrations of substrate.

Irrespective of which of the factors mentioned here are responsible for the drop of the CFSTR efficiency, it is very difficult to restore the reactor efficiency to the level required. This may be achieved by extension of the retention time to a value higher than $\tilde{\Theta}_u$ and, as soon as the efficiency required is reached, by the return to shorter times (down to a level of $\tilde{\Theta}$).

However, if the biomass has been killed, a high reactor efficiency will not be recovered until a new culture is grown.

It should be mentioned that extending the retention time, we have to discharge great amounts of wastewater immediately to the receiving stream without biological treatment. To avoid this, it seems advisable to work with sufficiently long retention times, i.e., greater than $\tilde{\Theta}_u$. Needless to say that this should be preceded by economic analysis (increased overall dimensions of the CFSTR and, consequently, higher capital cost, etc.).

## 5. ELIMINATING AN UNSTABLE OPERATION OF THE CFSTR

For certain parameters values the $\tilde{S}_2$ versus $\tilde{\Theta}$ curves show no local extremes (as can be seen in fig. 4b). In other words, for these values the multiplicity of steady-states does not occur, thus some undesirable consequences (e.g., rapid decrease in the efficiency of the CFSTR) can be avoided. Such a situation is of significance for practical purposes, and it seems worth considering what are the requirements to comply with (especially concerning the process parameters $\tilde{S}_1$, $k$, $c$, $\tilde{X}_D$, $\alpha$) in order to achieve favourable effects.

A similar problem was considered by CHI and co-workers [5] for a chemostat. In their study, they made the following assumptions: no biomass is present in the influent, the process does not involve recirculation, and the maintenance coefficient equals zero. These are strong simplifications, and in practice (particularly at high efficiencies which are striven for everywhere) the utilization of the substrate for maintenance is comparable with, and in some instances even higher than, the utilization of the substrate for biomass growth.

The attempt to solve the problem of interest without making simplified assumptions causes certain trouble. The procedure is quite complex and has been presented in a separate report [15].

Based on the results discussed there, we may state that the values of the parameters $\tilde{X}_E = (1+\alpha)\tilde{X}_D$, $k$, and $\tilde{S}_1$ seem to exert a substantial effect on whether or not the $\tilde{S}_2$ versus $\tilde{\Theta}$ plot will have a desirable shape. Thus, the parameter $\tilde{X}_E$ describes both the quantity of the biomass entering the CFSTR and the method of entering, and $k$ denotes the degree of inhibition due to the substrate. It is of interest to mention that $k = 0$ holds for those substrates alone which involve a $\mu$ versus $S_2$ relationship obeying the Monod equation. As shown in an earlier report [5], at $\tilde{X}_E = 0$ (which means that no biomass is immobilized on the carrier, i.e., $X_A = 0$, no biomass is contained in the influent, i.e., $X_1 = 0$, and no biomass is recirculated, i.e., $X_{5,Q} = 0$) the $\tilde{S}_2$ versus $\tilde{\Theta}$ relationship will have an advantageous plot only for those concentrations of substrate in raw wastewater which satisfy the condition

$$k\tilde{S}_1^2 \leqslant 1. \tag{10}$$

But this condition is fulfilled when the values of $\tilde{S}_1$ are relatively low. For higher concentration values the plots will be advantageous when $\tilde{X}_E > 0$. However, once certain limit values of $\tilde{S}_1$ have been reached, the curve will show a disadvantageous plot even if $X_E = +\infty$. These limit values of $\tilde{S}_1$ can be calculated from eq. (11) when adopting fixed values for the parameters $c$ and $k$:

$$ck^2 y^4 + 2k(1+c)y^3 + (1+c+2kc-k\tilde{S}_1)y^2 + 2cy + \tilde{S}_1 + c = 0 \tag{11}$$

where:

$$y = A\cos\frac{B}{3} - D,$$

$$A = \frac{[3(1+c)^2 - 2wc]^{1/2}}{3^{1/2}ck},$$

$$B = \arccos\frac{-3(3^{1/2})(1+c)^3 - w(1+c)c + 2c^3k}{[3(1+c) - 2w]^{3/2}},$$

$$D = \frac{1+c}{2ck}, \qquad w = 1+c+2ck-k\tilde{S}_1.$$

It may be proved that there exists only one value of $\tilde{S}_1$ which has a physical meaning and fulfils eq. (11) [15]. For $\tilde{S}_1$ values ranging between those calculated from eq. (10) and those obtained from eq. (11) we can determine the minimum value of $\tilde{X}_E$ ($\tilde{X}_{E,\min}$) to ensure the advantageous plot of the $\tilde{S}_2$ versus $\tilde{\Theta}$ relationship.

$\tilde{X}_{E,\min}$ value can be calculated from eq. (12)

$$\tilde{X}_E = \frac{(\tilde{S}_1 - \tilde{S}_2)^2(k\tilde{S}_2^2 - 1)}{2k\tilde{S}_2^3 + \tilde{S}_2^2(1-k\tilde{S}_1) + c(1+\tilde{S}_2+k\tilde{S}_2^2)^2 + \tilde{S}_1} \tag{12}$$

after having substituted the root of eq. (13) contained in the interval $[0, \tilde{S}_1]$ for $\tilde{S}_2$.

$$a_5\tilde{S}_2^5 + a_4\tilde{S}_2^4 + a_3\tilde{S}_2^3 + a_2\tilde{S}_2^2 + a_1\tilde{S}_2 + a_0 = 0 \tag{13}$$

where:

$$\begin{aligned} a_0 &= \tilde{S}_1 + \tilde{S}_1 c + c, & a_3 &= k(2+k\tilde{S}_1 c - 1 - 4c), \\ a_1 &= c + \tilde{S}_1 + \tilde{S}_1 c + 3k\tilde{S}_1 c, & a_4 &= -k(1+c+3ck+k\tilde{S}_1 c), \\ a_2 &= k(4c\tilde{S}_1 + \tilde{S}_1 - 2c), & a_5 &= -k^2(1+c+k\tilde{S}_1 c). \end{aligned}$$

It can be proved that there exists only one root of this kind [15].

Figure 5 gives $\tilde{S}_1$ versus $k$ relationship for different value of $\tilde{X}_E$, the value of $c$ being 0.06. The curves were calculated from eqs. (10), (11), and (12) with the use of an ODRA-1325 computer. Based on the relationship plotted for different values of $c$ it is possible to determine whether or not the shape of the $\tilde{S}_2$ versus $\tilde{\Theta}$ curve will be favourable. If a point having coordinates $k$, $\tilde{S}_1$ belongs to region I, the $\tilde{S}_2$ versus $\tilde{\Theta}$ curve will have a disadvantageous plot irrespective of the $\tilde{X}_E$ value. When such a point is included in region III, the plot will be always advantageous even for $\tilde{X}_E = 0$. For the points in region II, the plots depend on the value of $\tilde{X}_E$ and the advantageous plot is obtained when $\tilde{X}_E$ value is high enough.

Using graphs like those in fig. 5 is not convenient. This is because of great reading errors of the $k$, $\tilde{S}_1$ and $\tilde{X}_E$ values when logarithmic scales are used. Furthermore, for engineers, of importance is to know the $\tilde{X}_{E,\min}$ value which ensures stable operation for given $\tilde{S}_1$, $k$ and $c$. Such an information cannot be drawn from fig. 5 exactly enough. For those reasons, the numerical solutions of eq. (11), for $k$ and $c$ ranging from 0.001 to 1.0 and from 0 to 1.0, respectively, were approximated by eq. (11a).

$$\tilde{S}_1 = \exp[0.024(\ln k)^2 - 0.6039\ln k + 1.8908] + c\cdot\exp[0.0459(\ln k)^2 - 0.3311\ln k + 2.7659]. \tag{11a}$$

This equation enables one to calculate a limit value of $\tilde{S}_1$ above which nonstability exists even for $\tilde{X}_E = +\infty$. It is evident from eq. (11a) that higher values of $\tilde{S}_1$ are obtained when substrate used for maintenance is taken into account ($c > 0$). Neglecting maintenance ($c = 0$) gives lower values. For $k = 0.1$ it is possible to calculate the values 30.1 and 38.6 when adopting $c = 0$ and $c = 0.2$, respectively. For $K_S = 20$ gm$^{-3}$ it gives the limit values 600 and 772 gm$^{-3}$, respectively.

For the given values of $k$ and $c$, with $\tilde{S}_1$ between those calculated from eqs. (10) and (11) or (11a), one can calculate $\tilde{X}_{E,\min}$ using a simple programme in BASIC included in this paper. For $k = 0.1$ and $\tilde{S}_1 = 30$ the calculated $\tilde{X}_{E,\min}$ values are 5084.5 and 65.1, for $c = 0$ and $c = 0.2$, respectively. Adoption of $Y = 0.5$g ss g$^{-1}$ and $K_S = 20$ g m$^{-3}$ gives the $X_{E,\min}$ values 50845 and 641 g ss m$^{-3}$. Thus, it is evident that the omission of maintenance [5] leads to highly erroneous predictions of the $X_{E,\min}$ values. It appears that these errors become higher when $\tilde{S}_1$ approaches its limit values from eqs. (11), or (11a).

Since

$$\tilde{X}_E = (1+\alpha)\tilde{X}_A + \tilde{X}_1 + \tilde{X}_{5,Q}, \tag{14}$$

the value of $\tilde{X}_E$ can be increased by increasing the values of the parameters $\tilde{X}_A$ and/or $\tilde{X}_1$, and/or $\tilde{X}_{5,Q}$, and/or $\alpha$.

From eq. (9) it follows that the increase in the values of the parameters $\tilde{X}_A$, $\tilde{X}_1$ or $\tilde{X}_{5,Q}$ leads to the decrease of the HRT required to obtain a fixed concentration of the substrate in the reactor effluent. Thus, increasing the values of these parameters brings about an intensification of the treatment process. But a large increment of $\tilde{X}_1$ seems to be disputable, as in such a situation the CFSTR has to be continuously fed from outside with substantial amounts of the biomass. Moreover, when the $\tilde{X}_1$ value increases, so does the suspended solids concentration in the influent to the secondary settling tank (eq. (6)), which calls for an increase of its overal dimensions. Increment of $\tilde{X}_{5,Q}$ may be achieved by increasing $X_5$ value, i.e., increasing the secondary settling tank dimensions. There is no need to increase the dimensions of the secondary settling tank when the biomass concentrations are high, but the biomass itself is immobilized on a carrier. If the $\tilde{X}_A$ values are sufficiently high, we need not recirculate ($\tilde{X}_{5,Q} = 0$) or supply the biomass from outside the system ($\tilde{X}_1 = 0$). Furthermore, a biomass immobilized on a granular carrier or on a fixed packing of the CFSTR will be easily retained in the reactor. This being so, a secondary settling tank is unnecessary or may be quite small in size.

When $\tilde{X}_A \neq 0$, the value of $\tilde{X}_E$ can be increased by increasing the recirculation ratio $\alpha$. Although this eliminates an unstable operation of the CFSTR, the HRT required to ensure a satisfactory treatment efficiency will have to be substantially extended. On the other hand, a considerable increase of the recirculation ratio increases the costs of pumping. Thus, for these reasons it does not seem advantageous to increase the ratio of recirculation in order to obtain such $\tilde{X}_E$ values that would be high enough for our purpose.

## 6. INCOMPLETE ELIMINATION OF UNSTABILITY IN THE OPERATION OF A CFSTR

As far as the points included in the top part of region II are concerned (fig. 5), a complete elimination of unstability requires very high values of $\tilde{X}_E$. In engineering practice such values cannot be achieved for the reasons considered earlier. This being so, we may aim at incomplete eliminating the unstability by decreasing the value of $\tilde{\Theta}_u$ (fig. 4) to the lowest advantageous level and employing HRTs higher than $\tilde{\Theta}_u$. The same holds for the points contained in region I. As shown by SZETELA [15], increasing the values of $\tilde{X}_A$, $\tilde{X}_1$ and $\tilde{X}_{5,Q}$ gives a decrease in the value of $\tilde{\Theta}_u$. When the recirculation ratio increases, so does $\tilde{\Theta}_u$, which is not advantageous for the purpose considered here.

An unstable operation of the CFSTR can be either completely or partly eliminated by decreasing the concentrations of the substrate in the influent (raw wastewaters). This may be achieved either by the addition of wastewater which does not contain inhibitory substrates or by dilution with water (e.g., supplied from the recipient stream). If the influent has to be diluted, it becomes necessary to improve the removal efficiency, as otherwise the recipient stream (e.g., a river) will receive additionally increased pollution loads. It can be proved [15] that the product of HRT and flow rate (increased due to the dilution of the influent) will be higher than in an operation with no admixtures added to the feed. It means that an increase in the degree of dilution brings about increase in the required reactor volume. Consequently, admixture with adequate amounts of wastewater or water makes heavy demands on the overall dimensions of both the CFSTR and the secondary settling tank.

## 7. CONCLUSIONS

Wastewaters containing degradable inhibitors of microorganisms growth may be responsible for an unstable operation of the CFSTR involved in the biological treatment process. This unstability occurs only in a certain range of HRT, and the limits of the interval are influenced by the process parameters ($\tilde{S}_1$, $k$, $c$, $\tilde{X}_D$ and $\alpha$).

The operation of the CFSTR with HRTs, at which this instability occurs, leads either to a significant decrease of the treatment efficiency or to the failure of the treatment process. The unstability of operation can be eliminated by increasing the concentration of the biomass in the influent (which is not usually feasible in engineering practice) or by the increase of the quantity of recirculated biomass. Both of the procedures have the disadvantage, consisting in the fact that the increase of the overall dimensions of the secondary settling tank becomes a necessity.

Increasing the recirculation ratio $\alpha$ will not eliminate the unstability of reactor operation without a considerable increase of its overall dimensions. Thus, the most favourable procedure is to increase the concentration of the biomass immobilized on the carrier which, in addition, permits decreasing the overall dimensions of both the CFSTR and the secondary settling tank.

When the influent concentrations of the substrate are high, the only method yielding a complete elimination of the process unstability is the dilution of the incoming raw wastewater. However, this effect will not be achieved, either, without a significant increase in the dimensions of the CFSTR and the secondary settling tank.

*Translated by Janina Kosińska*

*PROGRAMME "XEMIN FINDING"*

```
1Ø REM XEMIN = X̃E,min, S1 = S̃1, C = c, K = k
2Ø INPUT S1
3Ø INPUT K
4Ø INPUT C
5Ø LET B$ = "-((S1-W)*(S1-W)*(K*W*W-1))/(2*K*W*W*W
         +W*W*(1-K*S1)+S1+C*(1+W+K*W*W)*(1+W+K*W*W))"
```

```
60 LET A12 = 0
70 LET A13 = S1
80 LET W = A12
90 LET H = (A13 - A12)/100
100 LET H1 = H
110 LET E1 = H*1E-7
120 LET D = VAL B$
130 LET C1 = D
140 LET W = W + H1
150 IF W < A13 THEN GOTO 170
160 LET XEMIN1 = A13
170 LET D = VAL B$
180 IF D < C1 THEN GOTO 130
190 LET H1 = -H1/2
200 IF ABS H1 > E1/2 THEN GOTO 130
210 LET XEMIN1 = W
220 PRINT "XEMIN = "; -VAL B$
230 STOP
```

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## BIOLOGICZNE OCZYSZCZANIE ŚCIEKÓW Z SUBSTRATAMI INHIBITUJĄCYMI

Przy biologicznym oczyszczaniu niektórych rodzajów ścieków przemysłowych występują pewne specyficzne problemy. Są one związane z obecnością w ściekach biodegradowalnych substratów, które inhibitują wzrost mikroorganizmów. Oczyszczanie takich ścieków osadem czynnym w komorach o pełnym wymieszaniu związane jest z poważnymi niedogodnościami eksploatacyjnymi. Wynika to z występowania zjawiska niestabilnej pracy komory w pewnym zakresie czasów przetrzymywania. W takich warunkach sprawność oczyszczania może ulegać znacznym zmianom przy niewielkich zmianach parametrów procesu. W pracy przedstawiono związek tej niestabilności ze stężeniem substratów inhibitujących w oczyszczanych ściekach, niektórymi parametrami procesu i parametrami kinetyki mikrobiologicznej.

Z przedstawionych rozważań wynika, że w określonym zakresie stężeń ścieków surowych istnieje możliwość wyeliminowania niestabilnej pracy komory. Przeanalizowano możliwości eliminacji niestabilności przez: 1) intensywną recyrkulację ścieków oczyszczonych z osadnika wtórnego, 2) doprowadzanie biomasy spoza układu do dopływających ścieków surowych, 3) rozcieńczanie ścieków surowych wodą lub ściekami bez substratów inhibitujących, 4) unieruchamianie biomasy na nośniku w komorze osadu czynnego. Stwierdzono, że najbardziej efektywną metodą jest unieruchamianie biomasy.

## БИОЛОГИЧЕСКАЯ ОЧИСТКА СТОЧНЫХ ВОД ОТ ИНГИБИТОРНЫХ СУБСТРАТОВ

Некоторые промышленные сточные воды создают серьёзные проблемы во время их биологической очистки. Это вызвано присутствием биодеградируемых ингибиторных субстратов, которые могут тормозить рост микроорганизмов, особенно тогда, когда выступают в больших концентрациях. Неотъемлемым недостатком очистки таких сточных вод в процессе активного ила в резервуаре с непрерывным питанием и перемешиванием является нестабильность процесса в некотором интервале времени выдержки. В обсуждаемых исследованиях эта нестабильность связана с начальными концентрациями загрязнений, с некоторыми параметрами процесса, а также с параметрами микробиологической кинетики.

Из теоретических рассуждений следует, что в определённых пределах загрязнений сырых сточных вод, удовлетворив некоторым условиям, можно избежать нестабильной работы реактора. Анализу подвергались следующие методы: 1) интенсивная рециркуляция стока из вторичного отстойника, 2) подвод биомассы извне системы к вливающимся сточным водам, 3) разбавление подведённых сточных вод или водопроводной водой, или коммунальными сточными водами, не содержащими ингибиторных субстратов, 4) иммобилизация биомассы на носителе в резервуаре активного ила. Отмечено, что наиболее эффективным методом является иммобилизация биомассы.