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PERFORMANCE AND DESIGN OF A SELECTOR FOR BULKING CONTROL

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ABSTRACT

Experimental data from continuous-flow activated-sludge reactors with selectors fed with highly biodegradable, soluble feed were correlated using a simple, semi-empirical formula. Rate of the substrate removal in the selector was demonstrated to be a function of the organic loading in the initial mixing chamber. The formula allows prediction of the substrate concentration in the selector and was used for the optimization of the selector's design for bulking control. Analysis of the equation demonstrated that an optimum sludge recycle rate exists for a set of systems parameters. The optimum recycle rate is always less than 100 percent and approaches this value as the system constant decreases. The substrate concentration in the contactor at the optimum sludge recycle rate is equal to one-half of the influent concentration.

KEYWORDS

Activated sludge process, bulking sludge, selector design, bulking control.

INTRODUCTION

The growth of filamentous organisms in continuous-flow, low F/M activated sludge systems has been shown to be suppressed by a low degree of longitudinal mixing or the introduction of an initial compartment (selector) for the mixing of return sludge and influent (Chudoba et al., 1973b; Tomlinson et al., 1979; Rensink et al., 1982 and Lee et al., 1982). Chudoba et al. (1973a) developed a theory of a selector which promotes growth of floc-forming, nonfilamentous bacteria. Their concept explains the selection of bacterial species based on differences in growth constants in the Monod formula, which would favor filamentous bacteria at the lower substrate concentrations (Figure 1). The theory was verified directly for two species of filamentous bacteria (Van den Eynde, 1982 and Van Veen, 1982) and indirectly for bulking and non-bulking heterogeneous cultures for a variety of specific substrates (Chudoba et al., 1985).

THEORETICAL CONSIDERATIONS

In an attempt to optimize the design of the selector two important factors need to be considered. One of them is the substrate concentration in the selector. From the already verified theory, the higher the substrate concentration the more favorable is the growth rate (or substrate uptake) of the floc formers in their competition with the filamentous bacteria. From published data (Chudoba et al., 1985) it appears that for most of the individual substrates a cut-off concentration, at which floc formers have a higher growth rate than the filaments, is below 5 mg/l.

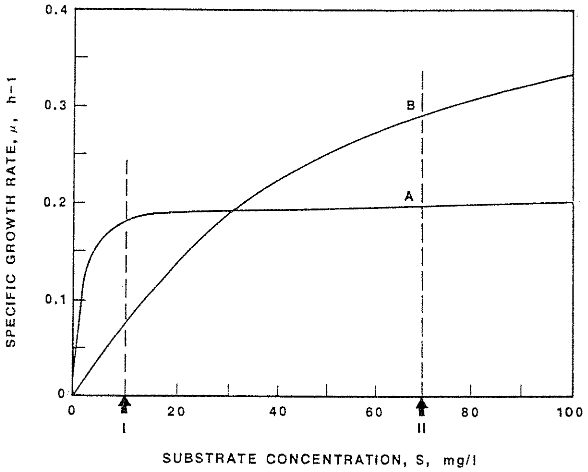

FIGURE 1 - GRAPHICAL PRESENTATION OF THE PRINCIPLE OF SELECTION OF MICROORGANISMS IN MIXED CULTURES. A-FILAMENTOUS BACTERIA, B-FLOC FORMERS (AFTER CHUDOBA ET AL., 1973 a)

In any case, the assumption can safely be made that the higher the substrate concentration in the selector the better chance the floc formers will have to successfully compete with the filamentous species.

The second factor involved is the fraction of the substrate removed in the selector. Obviously, if the selector efficiency is low, the majority of the substrate passes to the main aeration tank. In such circumstances the selector will not serve its purpose, even if the substrate concentration in it is high, since the bulk of the substrate will be removed at the prevailing low concentrations of the main aeration basin favoring the filaments. At the same time, if the selector's removal efficiency is high, the substrate concentration in the selector will be necessarily lowered, working against the high substrate concentration requirement.

In order to balance these two conflicting requirements, the weighted average substrate concentration (biosorption concentration - C_B) at which the substrate was removed is proposed to be an optimization parameter. For a system consisting of two completely mixed tanks (selector and aeration basin) the formula for the weighted average reactant concentration has the following form.

$$C_B = C_1E + C_2(1-E) \qquad (1)$$

where:

C_B = weighted average concentration at which substrate is removed in the system (biosorption concentration)
C_1 = biodegradable substrate concentration in the selector
C_2 = biodegradable substrate concentration in the aeration basin
E = fraction of the substrate removed in the selector.

For most cases, the biodegradable substrate concentration in the aeration basin is negligible, and Equation 1 reduces to:

$$C_B = C_1E \qquad (2)$$

It is proposed that the criterion for optimization of the selector design is to maximize the value of C_B. For a solution of the problem a relationship between the selector operating parameters and its removal efficiency (and consequently C_1) must be known.

The objective of the study was to develop relationships which can satisfactorily describe the substrate removal rate in the selector and can subsequently be utilized for optimization of the selector design for bulking control.

MATERIALS AND METHODS

Reactor Operation

During the study six continuous-flow and one batch reactor were operated. All the reactors were operated at the same overall F/M and were fed with the same influent. The influent consisted of nutrient broth (BBL Microbiology Systems), yeast extract and dextrose (D-glucose), micronutrients and bicarbonate. Feed concentrate was prepared as needed (approximately once per month) and stored in a refrigerator. Fresh feed solution was made up daily from the concentrate using tap water.

The continuous-flow reactors consisted of 14.5 l aeration chambers separated from the effluent section by a baffle made from filtering cloth. The aeration basins in all the reactors were aerated intermittently. The cycle time was 3 hr with a 75 min aeration period and 105 min air-off period which provided 50/50 distribution of aerobic and anoxic conditions. During the air-off time, the aeration chamber contents were stirred with nitrogen gas from a cylinder.

Five of the continuous-flow reactors were equipped with selectors. Four of the selectors were continuously aerated with continuous sludge recycle, while the fifth remained quiescent during the air-off cycle. In addition to the six continuous reactors, a 5 l, intermittently aerated, batch-fed reactor was also maintained. The reactor was fed once a day with concentrated feed at the same overall F/M as the continuous-flow reactors. Table 1 summarizes the operational parameters of the reactors and selectors.

TABLE 1

OPERATIONAL PARAMETERS OF THE REACTORS

Parameter	Reactor						
	1	2	3	4	5	6	7
Mode of Feed Addition	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Batch
Mode of Aeration							
Aeration Basin	Intermittent	Intermittent	Intermittent	Intermittent	Intermittent	Intermittent	Intermittent
Selector	N/A	Intermittent	Continuous	Continuous	Continuous	Continuous	N/A
Sludge Recycle	N/A	Intermittent	Continuous	Continuous	Continuous	Continuous	N/A
F/M, BOD_5 Basis	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Influent BOD_5, mg/l	298	298	298	298	298	298	[a]
Influent COD, mg/l	420	420	420	420	420	420	[a]
Reactor Volume, l	14.3	14.2	14.4	14.4	14.4	14.5	5
Selector Volume, ml	--	970	970	440	1,100	295	--
Influent Flow Rate, ml/min	9.9	10.5	10.6	10.3	10.6	10.2	--
Sludge Recycle Rate, ml/min	--	111	111	44.3	44.3	26.6	--
HRT in Reactor, hr	24	24	24	24	24	24	24
HRT in Selector, min	--	8	8	8	20	8	--
MLVSS	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Floc Load in Selector, mg COD/g VSS		--	20	20	50	50	80

[a] Fed with feed concentrate.

Experimental Procedures

During the experimental work, the selector's performance in terms of COD removal efficiency was routinely monitored. The sample taken from the selector was immediately centrifuged in order to separate the liquid phase from the bulk of the biomass, and subsequently filtered through Whatman AH-934 fiberglass filters. After each sampling event a minimum of three HRTs were allowed to elapse before the sampling was repeated.

Analytical Methods

Substrate concentration in this study was measured as COD, using the semimicro, closed reflux, titimetric method (Standard Methods, 1985). Special calibration procedures and correction factors used to improve test accuracy are described in detail elsewhere (Patoczka, 1988). Other parameters reported in this study (stirred-zone settling velocity) were performed according to Standard Methods.

SUBSTRATE REMOVAL KINETICS IN THE SELECTOR

From the steady-state substrate mass balance around the selector (assuming no growth) the following formulas apply with nomenclature shown in Figure 2.

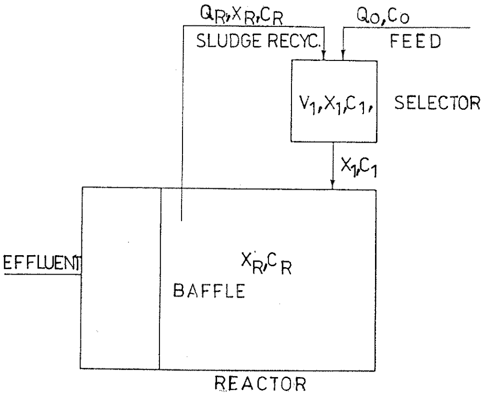

FIGURE 2 - GRAPHICAL PRESENTATION OF THE NONMENCLATURE USED

Floc loading (F) = $Q_oC_o/(Q_RX_R)$ (adopted from Eikelboom, 1982) (3)

Floc uptake (B) = $[Q_oC_o + Q_RC_R - (Q_o+Q_R)C_1]/(Q_RX_R)$ (4)

Substrate efficiency removal (E) = (B/F) 100 (5)

Specific reaction rate in the selector (R_r) = $[Q_oC_o + Q_RC_R - (Q_o+Q_R)C_1]/(VX_1)$ (6)

The average performance of each reactor's selector is shown in Figure 3 as a function of the average floc loading and HRT in the selector, indicating, as expected, that increased floc loading at the constant HRT results in a lower substrate removal efficiency. During a separate experiment, the HRT and floc load of the selector in Reactor No. 4 were changed at relatively short time intervals (1 to 2 hr). A graph constructed from data collected during this intensive study (Figure 4) gives a more complete picture of the relationship between the selector's operating parameters and its performance. While the results presented in Figure 4 provide a consistent series of curves, they are valid only for the specific substrate and other parameters used during the operation of the tested reactors.

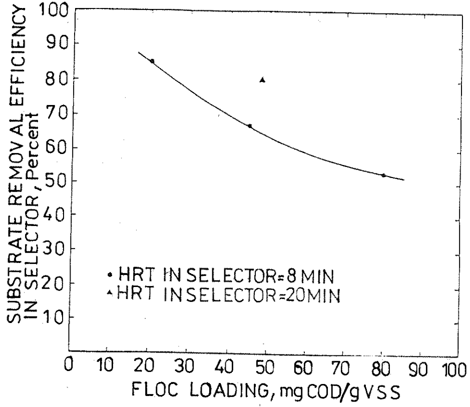

FIGURE 3 - CORRELATION BETWEEN AVERAGE SUBSTRATE REMOVAL EFFICIENCY IN SELECTOR AND FLOC LOADING

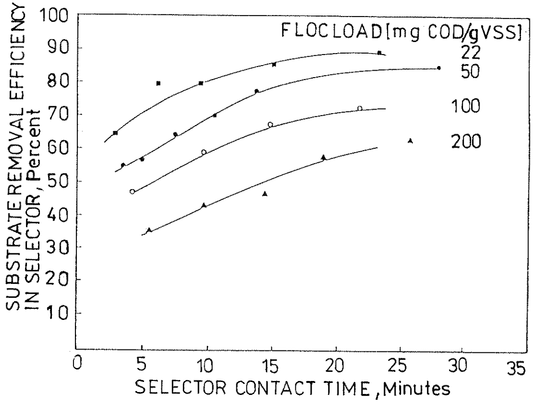

FIGURE 4 - CORRELATION BETWEEN SUBSTRATE REMOVAL EFFICIENCY IN SELECTOR AND HYDRAULIC RETENTION TIME (REACTOR NO. 4)

In order to develop a more general relationship the selector performance data were correlated using a semi-empirical function similar to the one proposed by Suschka (1980) for a completely mixed activated sludge system. The proposed model has the following form:

$$R_r = R_m(F/M)/(K_w+F/M) \qquad (7)$$

where:

R_r = reaction rate in the selector, gCOD removed/gVSS-day
$F/M = C_oQ_o/(Q_RX_Rt)$ = organic loading in selector, gCOD/gVSS-day
R_m = maximum reaction rate, gCOD/gVSS-day
K_w = half-velocity loading, gCOD/gVSS-day.

Correlation of the performance data from the intensive study in reactor No. 4 using a linearized form of Equation 7 is shown in Figure 5. The resulting equation is:

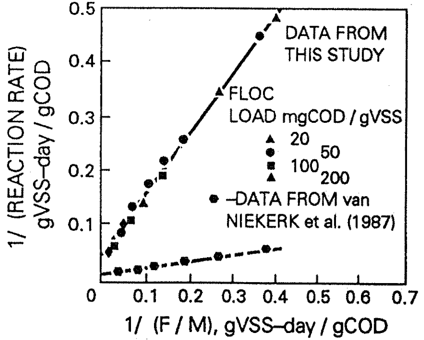

FIGURE 5 - CORRELATION OF SELECTOR PERFORMANCE DATA

The resulting equation is:

$$1/R_r = 1.089\ (F/M) + 0.0428 \qquad (8)$$

with correlation coefficient of 0.995.

Recalculation of the constants gives the final formula for modelling the selector efficiency in Reactor No. 4.

$$R_r = \frac{23.4\text{g/g-day} \cdot F/M}{25.5\text{g/g-day} + F/M}, \text{ gCOD removed/gVSS-day} \qquad (9)$$

The maximum reaction rate appearing in Equation 9 was shown to be close to the true initial maximum reaction rate for a given sludge-substrate system, as independently determined from the parallel batch and FBR tests performed on sludge from the same reactor.

In addition to the data from this study only one set of complete selector performance data allowing correlation using Equation 7 was found in the literature (Van Niekerk et al., 1987). Correlation of these data is illustrated in Figure 5, demonstrating a good agreement with the proposed model.

The use of Equation 7 can be supported by the following theoretical considerations applicable to any biological system.

The reaction rate in any bacterial culture can not exceed a limiting, maximum rate, corresponding to the rate of the limiting reaction or transport step. In this case the most probable limiting factor is a finite amount of enzymes available and/or limited bacteria surface (active sites) which control the substrate's transport through the cell's membrane. Both phenomena are characteristic of catalytic and heterogeneous reactions. Obviously, the activated sludge process fits into both categories, considering that enzymes are in fact biocatalysts. The maximum reaction rate is specific for a given microbial culture and substrate type. Continuous (or intermittent) exposure to a high substrate concentration can likely result in a physiological adaption of the culture and/or in a change in the bacterial species distribution. This will result in a somewhat higher maximum reaction rate for the culture, though there is still a limiting maximum specific reaction rate attainable for the biological assimilation of a given substrate mix.

At the other end of the spectrum, at very low substrate concentrations (loadings), the system's performance is bound to approach complete substrate removal and the observed reaction rate will correspond to the applied loading. This is particularly true when the loading rate is expressed in terms of biodegradable substrate such as BOD_5 or, as in the case of this study, in terms of biodegradable COD.

The simplest mathematical expression for the reaction rate embracing the two above discussed bounder conditions has the form of Equation 7 with $K_w = R_m$. The maximum reaction rate (R_m) appears in both numerator and denominator to fulfill the condition that for loads approaching zero the reaction rate is equal to the load.

OPTIMIZATION OF THE SELECTOR DESIGN

Model Development

As proposed previously, the average concentration at which the substrate is removed in the selector - reactor system (Formula 2) is proposed to be the optimization criterion for system's resistance to bulking. Values of C_B obtained from the reactors studied in this investigation are shown on Figure 6 as a function of time for which the reactor resisted bulking. Bulking is defined here as a condition where the ZSV is below 2 ft/hr. Besides five continuous-flow reactors with selectors, Figure 6 includes data from the continuous-flow reactor without a selector and from the batch reactor. Figure 6 supports the proposition that the higher value of C_B the greater reactor's resistance to bulking.

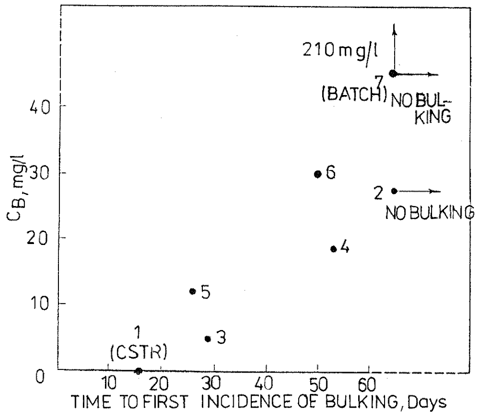

FIGURE 6 - RELATIONSHIP BETWEEN WEIGHTED AVERAGE BIOSORPTION CONCENTRATION (C_B) AND REACTOR'S RESISTANCE TO BULKING (REACTOR NO. IS INDICATED ON THE GRAPH)

From Equation 7, expressions for the calculation of the substrate concentration in a selector and the selector's substrate removal efficiency can be readily derived. The following relationships hold with nomenclature as given in Figure 2:

$$C_1 = C_oD - R_rX_1t \qquad (10)$$

where:

C_1 = available substrate concentration in the selector
C_o = influent substrate concentration
$D = Q_o/(Q_o+Q_R)$ = dilution rate
$X_1 = X_RQ_R/(Q_R+Q_o)$ = sludge concentration in the selector (neglecting growth)
t = hydraulic retention time in the selector.

Incorporation of Equation 7 into Equation 10 yields the equation for the biodegradable substrate concentration in the selector:

$$C_1 = [D^2C_o^2/X_R + DC_oK_w(1-D)t - R_mC_oD(1-D)t]/[DC_o/X_R + K_s(1-D)t] \qquad (11)$$

The value of K_w can be related to R_m:

$$K_w = aR_m \qquad (12)$$

Where a is a dimensionless constant, in most cases close to unity.

Rearrangement of Equation 11 yields:

$$C_1 = C_o[D^2+AD(1-D)(a-1)t]/[D+a(1-D)dAt] \quad (13)$$

Where:

A = system constant = R_mX_R/C_o

The efficiency of substrate removal in the selector is related to C_1 as follows:

$$E = (DC_o-C_1)/(DC_o). \quad (14)$$

Substitutions yield

$$E = A(1-D)t/[D + a(1-D)At]. \quad (15)$$

Incorporation of Equation 13 and 15 into the expression for the average biosorption concentration (Equation 2) yields:

$$C_B = C_oA(1-D)t[D^2+AD(1-D)(a-1)t]/[D+a(1-D)At]^2 \quad (16)$$

Model Analysis

Examination of Equation 16 indicates that C_B is a function of two independent variables, the selector dilution rate, D, and its hydraulic retention time, t. All other parameters can be assumed constant for a given system and are lumped into the system number, A, and the constant, a.

In practical applications, the hydraulic retention time in the selector is limited by the physical and/or economic constraints. With the selector size limited by the physical constraints of the existing facility, or set by a designer, the problem of finding the optimum selector operating parameters is reduced to calculating the maximum of a function of one variable - dilution rate.

In such cases (selector volume constant), the hydraulic retention time in the selector will depend on the dilution rate. It is therefore convenient to use a nominal hydraulic retention time in the selector (T). The following holds:

$$T = V_1/Q_o = t/D. \quad (17)$$

Substitution into Equation 16 yields:

$$C_B = C_o(1-D)LD[1+L(1-D)(a-1)]/[1+a(1-D)L]^2 \quad (18)$$

where:

$L = TA$ = system constant = TR_mX_R/C_o.

For a special case, when a=1, the local maximum can be readily found and has the following form:

$$D_o = (L+1)/(L+2) \quad (19)$$

where:

D_o = dilution rate at which the maximum C_B is obtained.

Expressing the dilution rate in the more convenient form of the sludge recycle rate provides the following formula:

$$R_o = 100/(L+1), \text{ percent} \quad (20)$$

where: R_o is the optimum sludge recycle rate (as percent of the influent flow).

When the coefficient a does not equal 1, differentiation of the Equation 18 with respect to D yields a third-order function (in the numerator). Analytical solution of the resulting equation, while straightforward, is extremely tedious and it was found more practical to find the local maximum numerically for a matrix of system constants (L) and coefficients (a).

The results are presented in the form of a correlation (Figure 7) from which the optimum sludge recycle rate can be determined for given values of L and a. The graph shows that the optimum sludge recycle rate to the selector is always less than 100 percent, and approaches this value for the systems characterized by a low value of the system constant, L. The optimum sludge recycle rate is for practical purposes independent of a, particularly after considering that for most systems a is close to unity.

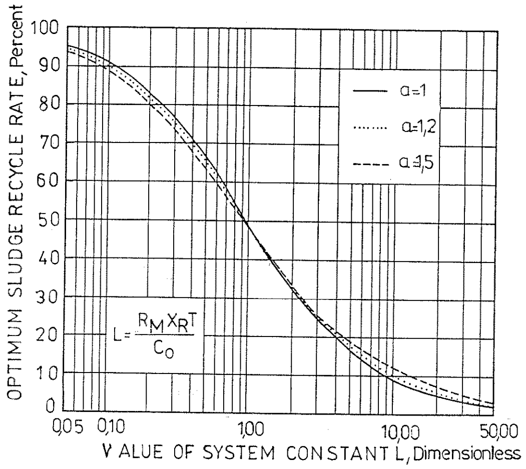

FIGURE 7 - CORRELATION FOR DETERMINATION OF OPTIMUM SLUDGE RECYCLE RATE

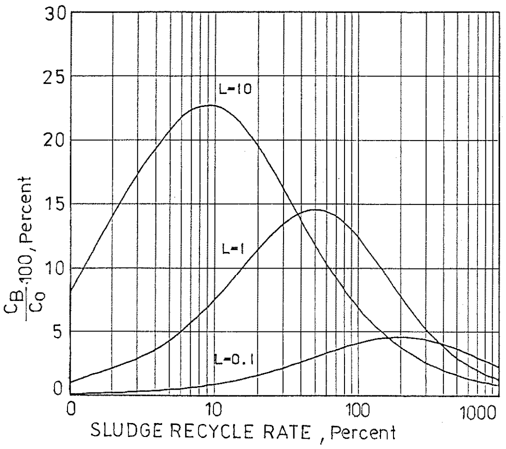

FIGURE 8 - AVERAGE SUBSTRATE CONCENTRATION AS A FUNCTION OF SLUDGE RECYCLE RATE

Further analysis of the model indicates that the selector operates at a maximum C_B when the substrate concentration in the selector is half that of the influent concentration. The efficiency of the substrate removal at the optimum sludge recycle rate is a function of L and increases asymptotically to 0.5 (50 percent) with an increasing system number.

In Figure 8, the values of C_B are plotted as a function of the sludge recycle rate for several values of L. Figure 8 illustrates that little premium can be gained by increasing the system number above about 10, since at this point the maximum C_B reaches 23 percent of the feed concentration (C_o), while the maximum obtainable C_B for the continuous-flow contactor is 25 percent of the C_o.

Model Limitations

It should be realized that the proposed model has been developed under several assumptions which limit its applicability.

Equation 7 describing the reaction rate in the selector as a function of F/M is felt to be applicable for any soluble substrate and for a wide range of F/M s in a selector. However, the equation was derived under an assumption that the biomass growth in the selector is negligible. Under high floc loads the biomass growth in the selector may be appreciable, and it could decrease the optimum sludge recycle rate for a given system.

Under extreme conditions (high floc-load, long HRT), Equation 7 may not describe accurately the reaction kinetics in the selector, since it would be out of the experimentally verified range. It is felt, however, that even in such a case the discrepancies from Equation 7 should be minor. This confidence is based on the previously discussed inherent validity of Equation 7 for the two boundary conditions (i.e., for low F/M, the R_r approaches F/M and for high F/M, R_r approaches R_m), and on the good fit of the experimental data presented in this study for the proposed formula.

A more critical area of concern is the applicability of Equation 7 for influents where a part of the substrate is in colloidal or particulate form. In this study a completely soluble substrate was used. Frequently, however, a substantial part of the available substrate is in a colloidal form, particularly in municipal wastewaters.

Apart from the considerations regarding the adequacy of Equation 7, more questions might arise concerning the selection of Equation 2 as the criterion of the selector optimization for bulking control. The most obvious limitation is the presence, at least in theory, of a minimum concentration at which the floc formers have a higher growth rate than the filamentous species. If conditions in the selector resulting from maximization of C_B are such that the substrate concentration C_1 is lower than the threshold concentration, proliferation of floc formers will not occur. At the same time it is unlikely that such a concentration can be defined for any real system, considering the multitude of species and substrates involved. At best, it may be demonstrated that a more adequate optimization criterion can be formulated.

At the same time, if the selector efficiency resulting from application of the model is much less than 50 percent, most of the substrate would leak into the aeration basin. In such cases it may be advisable to increase the recycle rate (efficiency), particularly if the resulting lower value of C_1 is still above the critical concentration for the given system. Unfortunately, such adjustments are possible only if the specific values of the growth parameters for floc formers and filamentous bacteria are available.

Finally, the proposed model addresses only low F/M bulking, which more correctly should be called low organic-substrate-concentration bulking. The proposed selector design procedure is aimed at creating in continuous flow, completely-mixed-system conditions in which the floc formers outgrow filamentous bacteria. Other methods of filamentous bulking control, such as selective killing with oxidants or by anaerobic (anoxic) selector are available but are not discussed here.

EXAMPLE

The proposed procedure for selector design can be illustrated by the following example.

A municipal treatment plant was expecting significant increase in the organic load due to a new industry discharge. The plant, operating at low F/M (0.20, BOD_5 basis), was generating poorly settling sludge with occasional, more serious bulking problems. Filamentous bacteria present confirmed that the settling problems were due to low F/M. Prior to accepting the new discharge, the plant was planning an expansion in order to continue operation at the design F/M. A possibility of improving sludge quality by converting an existing blending tank positioned in front of the aeration basin to a selector was investigated. The full-scale selector was designed in the following way.

Expected Flow = 2.95 mgd
Selector volume (existing blending basin) = 0.3 mil gal
Nominal HRT in the selector T = 0.3 mil gal/2.95 mgd = 0.10 day = 2.4 hr
Return sludge MLVSS = 3,500 mg/l
Influent soluble, biodegradable COD (estimated) = 1,000 mg/l
Maximum Reaction rate (assumed) = 15 gCOD/gVSS-day

$$L = \frac{0.10 \text{ day} \cdot 15 \text{ gCOD/gVSS-day} \cdot 3.5 \text{ gVSS/l}}{1 \text{ gCOD/l}} = 5.25$$

From Formula 20 (or Figure 7) R = 16 percent

Effectiveness of the selector in improving sludge settleability was demonstrated in a pilot-plant study. Measured available-substrate concentration in the selector was 41 percent of the influent concentration and substrate removal efficiency was 52 percent, indicating a good agreement with the design values. Consequently, the full-scale plant currently converts the blending basin to a selector with the above outlined design.

CONCLUSIONS

- The reaction rate in the selector was shown to be a simple function of the selector organic loading. The semi-empirical correlation derived from the experimental data has a form similar to the Monod-type equation with a maximum reaction rate and half-velocity loading being the functional parameters.

- The maximum reaction rate appearing in the equation for the reaction rate in the selector was close to the true initial maximum reaction rate for a given sludge-substrate system, as independently determined from batch and fed-batch tests.

- An average concentration at which the substrate is being removed in the selector-reactor system is proposed as a criterion for optimizing the selector's effectiveness for bulking control. The formula attempts to balance two conflicting requirements for a selector's effectiveness, i.e., high substrate removal efficiency and high substrate concentration in the selector. Experimental data from continuous-flow reactors support the proposed approach.

- Based on the formula for prediction of the reaction rate in the selector, and on the postulated relationship between the selector performance and resistance to bulking, a model for optimization of the selector design was developed. A resulting correlation allows the determination of the optimum sludge recycle rate for any set of the system's parameters lumped into a single system constant. The optimum sludge recycle rate results in a substrate concentration in the selector equal to one-half of the influent concentration. The optimum recycle rate is always less than 100 percent and approaches this value for small values of the system constant.

REFERENCES

Boyle, W. C. (1982) Water Pollution Research and Control, Proceedings of Conference Held in Cape Town, South Africa, Water Science and Technology, v. 14 (S) p. 953.

Chudoba, Cech, J. S., Farkac, J., and Grau, P. (1985) "Control of Activated Sludge Filamentous Bulking - Experimental Verification of a Kinetic Selection Theory," Water Research, v. 19, p. 191.

Chudoba, J., Grau, P., and Ottova, V., (1973a) "Control of Activated Sludge Filamentous Bulking. Part II - Selection of Microorganisms by means of a Selector," Water Research, v. 7, p. 1389.

Chudoba, J., Ottova, V., and Madera, V., (1973b) "Control of Activated Sludge Filamentous Bulking. Part I - Effect of Hydraulic Regime or Degree of Mixing in an Aeration Tank," Water Research, v. 7, p. 1163.

Eikelboom, D.H. (1982) "Biosorption and Prevention of Bulking Sludge by Means of a High Floc Loading," in Bulking of Activated Sludge: Preventive and Remedial Methods, ed. by B. Chambers and E.J. Tomlinson, Ellis Horwood Ltd., Chichester, G.B.

Houtmeyers, J., Van den Eyde, E., Poffe, R., and Verachtert, M. (1980) "Relation between Substrate Feeding Pattern and Development of Filamentous Bacteria in Activated Sludge Processes, Part I. Influence of Process Parameters," Env. Jour. Appl. Microbiol. Biotechnol, v. 9, p. 63.

Lee, S. E., Koopman, B. L., and Jenkins, D., (1982) Effect of Aeration Basin Configuration on Bulking at Low Organic Loading EPA Project Summary EPA-600/52-82-081.

Linne, S. R. and Chiesa, S.C. (1985) "Operational Variables Affecting Performance of the Selector - Complete Mix Activated Sludge Process," Presented at Annual WPCF Conference, Kansas City, MI.

Patoczka, J. (1988) "Performance and bulking control of Intermittently Aerated, Continuous-Flow Activated Sludge Systems with Selector," Ph.D. Dissertation, Vanderbilt University, Nashville.

Rensink, J. H., Donker, M. J. G. W., and Ijwema, T. S. J., (1982) "The Influence of Feed Pattern on Sludge Bulking," in Bulking of Activated Sludge: Preventive and Remedial Methods, ed. by B. Chambers, and E. J. Tomlinson, Ellis Honwood Ltd., Chichester G. B.

Suschka, J. (1980) "Biooxidation in a Continuous Activated Sludge Process,"Water Research, v. 14, p. 197-205.

Sykes, R. M. (1987) Discussion of "The Control of Bulking Sludge: From the Early Innovators to Current Practice" by O.E. Albertson, JWPCF v. 59, p. 172, in JWPCF, v. 59, p. 1079.

Tomlinson, E. J. and Chambers, B. (1979) "Methods for Prevention of Bulking in Activated Sludge," Wat. Pollut. Control, WPC v. 78, p. 524.

Van den Eynde, E., Houtmeyers, J. and Verachtert, H. (1982) "Relation between Substrate Feeding Pattern and Development of Filamentous Bacteria in Activated Sludge," in Bulking of Activated Sludge: Preventive and Remedial Methods, B. Chambers and E. J. Tomlinson editors, Ellis Norwood, Chichester, G. B.

Van Niekerk, A. M., Jenkins, D. and Richard, M. G. (1986) "A Mathematical Model of the Growth of Filamentous and Floc-Forming Organisms in Low F/M Activated Sludge Systems," presented at 59th WPCF Annual Conference, Los Angeles, CA.

Van Niekerk, A., Jenkins, D., and Richard, M.G. (1987) "Application of Batch Kinetic Data to the Sizing of Continuous-Flow Activated Sludge Reactors", Wat. Sci. Tech. v. 19, (3/4), p. 505.

Van Veen, W. L., Krul, J. M. and Bulder, C.J.E.A. (1982) "Some Growth Parameters of Haliscomenobacter hydrossis (syn. Streptothrix hyalina) a Bacterium Occurring in Bulking Activated Sludge," Water Research, v. 16, p. 531.