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RATIONAL DESIGN OF HIGH-RATE TRICKLING FILTERS, BASED ON EXPERIMENTAL DATA

Based on experimental results a new trickling filter design model is developed, and then tested against several types of wastewaters and filter media reported in literature. The model relates removal $S_e/S_a = \exp(-K/L)$ and is particularly suitable for the design of high rate plastic media trickling filters. It is demonstrated that the model efficiently replaces the conventional design models of Imhoff, Rincke, Galler and Gotaas and other empirical formulas, valid within an extremely narrow range of operational parameters.

Detailed design procedures are given with a notion that the design of all trickling filters should be based on lab or pilot scale data, if reliability of removal efficiency comparative to activated sludge is to be attained. Discussion of the attempts at developing a basic mechanic model for dominant trickling filter removal processes is presented.

NOMENCLATURE

k —	specific removal coefficient współczynnik prędkości redukcji zanieczyszczeń	(kg/m^{2}d)
n —	hydraulic exponent wykładnik hydrauliczny	(—)
q —	input flow rate natężenie dopływu	(m^3/s)
t —	time czas	(min)
A —	specific surface area of the media powierzchnia właściwa wypełnienia	(m^2/m^3)
H —	depth of the filter głębokość złoża	(m)
K —	gross removal coefficient ogólny współczynnik redukcji zanieczyszczeń	(kg/m^{3}d)
L —	volumetric organic loading applied obciążenie objętościowe ładunkiem organicznym	(kg/m^{3}d)
N —	recirculation ratio = Q_{rec}/Q_{raw} stosunek recyrkulacji	(—)
Q —	hydraulic loading per cross-section obciążenie hydrauliczne powierzchni przekroju	(m^3/m$^2\cdot$s)

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S_a — influent mixed applied concentration (g/m³)
stężenie ścieków zmieszanych, dopływających na złoże (g/m³)
S_e — effluent concentration (g/m³)
stężenie odpływu
S_0 — influent raw wastes concentration (g/m³)
stężenie ścieków surowych
S_x — intercept (d/m³)
przecięcie z osią S_e
T — temperature (°C)
temperatura
ΔT — T-20 (°C)
Θ — temperature correction (—)
współczynnik korekcji temperatury

1. INTRODUCTION

The introduction of oriented plastic media into the trickling filter practice has greatly supported the somewhat endangered popularity of the biological filters. The new media offered several advantages over conventional rock media, allowing a much greater removal of BOD per unit of volume, and application of larger hydraulic and organic loadings. Much greater filter depths are possible due to the structural properties of the plastic medium, without recourse to forced aeration. For superficial comparison the basic parameter is the specific surface area A. This may vary from A — 30 to 300 m^2/m^3, averaging 110 m^2/m^3. The actual performance is not directly related to A but depends on arrangement and configuration of the packing, voids ratio, etc. For example, most of the random packings will have higher A without slime than the corresponding oriented media. When the media become covered with the biological slime the situation may frequently be reversed. Due to bridging and ponding as well as due to irregular sloughing from the surface of the random medium, its effective specific surface, A_{eff}, may decrease markedly. These factors must be taken into account when comparing volumetric loadings to the filter.

The possibilities of using plastic media filters as roughing units and, conversely, as fining-nutrient removal units have yielded another advantage in competition with the activated sludge process.

2. STATEMENT OF THE PROBLEM

The reason for the increasing popularity of activated sludge over the trickling filters lies in the fact that activated sludge offered higher removal efficiencies and better correlation between the design computations and the full scale results.

At present, the designer of trickling filters is faced with at least a hundred of different models and empirical design formulas, as well as with several contradictory theories as to the role of individual parameters in treatment efficiency. Evaluation of the most frequently used design formulas [22] revealed that if a particular waste treatment case is considered and a trickling filter designed according to only four of the most popular models, then the volumes of media obtained by these models, may vary for the same conditions from 100 to 1300%, from model to model. Such "discrepancies" leave the designer with a very serious dilemma: which prediction will most closely represent the actual volume requirements?

This confusion is further increased by almost universal lack of agreement on some of the most fundamental practical issues in biological filtration, such as the effects of hydraulics, effects of recirculation, depth and organic loading. Presently existing models usually fail to represent the changes effected by variations in these parameters. As noted recently [18] there is evidence available in literature to both prove and disprove the benefits of recirculation, the detrimental effects of increased hydraulic loading, and increased concentration. These differences in opinions stem from the fact that various processes may be responsible for removal in various conditions.

3. TYPICAL MODELLING ATTEMPTS

The traditionally first approach was empirical and resulted in the so-called NRC formula [17]. This approach has been repeated several times since 1948 by such authors as RINCKE [23,], [24] or GALLER and GOTAAS [7], CUGW [2]; the latter formulas are quite frequently used by the design engineers in Poland.

The inadequacies of the empirical formulas resulted recently in search of mechanistic models based on actual purification processes in the biofilm. The unit processes usually modelled separately under an assumption that the given modelled activity is rate determining are the following:

1. The kinetics of the biochemical reactions which reduce the biochemical oxygen demand in the wastewater;
2. The transfer of oxygen from the gas phase to and through the liquid phase to the bacterial sites on the media;
3. The transfer of organic compounds and nutrients from the liquid to the bacterial slime on the trickling filter media.

The first mechanism involves such factors as slime acclimation, temperature, pH, "biodegradability" of substrate, substrate concentration, aerobic /anaerobic balance in the slime film and oxygen supply.

Based on the early work by Velz and later research by Sinkoff et all., ECKENFELDER has developed a final version of his popular time-dependent design model [6]:

$$S_e/S_a = \exp(-\mathrm{K}H^{1-m}/Q^n). \tag{1}$$

This equation related removal, S_e/S_a to depth and flow rate-in ratio where the two parameters are equivalent to the time, i.e. $S_e/S_a = \exp(-K't)$. The two new coefficients m and n were usually arbitrarily selected by designers as $m = 0$, $n = 0.5$. One may eventually agree with the assumption that the coefficient m — defining distribution, activity and composition of slime with depth is equal to zero, provided, however, that it is taken into account in the scale-up factor that converts pilot data into full-scale design. The coefficient n, however, has been studied by the author and found to be close to 0.5 for random-conventional media, and closer to 1.0 for uniform, oriented planar media [20]. Rational interpretation of the gross rate coefficient K is offered:

$$K = kA, \tag{2}$$

where k (L^3/L^2t) is the specific reaction coefficient and A (L^2/L^3) specific surface area.

The approach, taken by other researchers in modelling the kinetics, was oriented toward the well known Monod [16] equations which relate the substrate removal rate to the rate of biological growth of mass of organisms, incorporating the substration constant (K_s). Kornegay and Massey [12] have solved Monod's equations and arrived at an equation that must be solved by the trial and error method, hence is very impractical for design purposes.

Recent studies [18] by means of applying the Michaelis-Briggs-Haldane mechanism (the growth rate equation) have proved that the Monod approach to trickling filter design shows complete disagreement with the real-life results. The reason for failure of Monods equations is the fact that they were constructed for pure mono-cultures and not for complex mixtures, such as wastewaters.

The concept of super-high rate oxidation of biologically degradable substrate on the surface of the bacterial film (surface reaction) is mechanistically unsound. In a modern high- or super-rate filters the retention time may be as short as 2–10 minutes (depth 4–6 m) which is much less than the time required for any known biological reaction to take place. Biological flocculation and precipitation may be more likely the processes responsible for transferring the pollutional load to the film, followed by unloading of slime. It has been demonstrated recently that the sludge production in trickling filters can be successfully related to BOD removal, in a manner analogous to activated sludge [18] indicating the possible convergence of the activated sludge and the trickling filter theories.

This discussion leads to a conclusion that so far all attempts at mechanistic explanation of substrate removal through surface biological oxidation have failed, thus the approach that could offer a design equation should be of the empirical or curve-fitting type. If surface oxidation was solely responsible for the removal of BOD from the incoming wastes, than this mechanism would surely be the rate limiting step. This is concluded from the long research experience which revealed that rates of substrate consumption by bacterial communities are much slower than most of the physico-chemical reaction rates.

Finally, the direct proportionality between the applied load and load removed $(ML^{-3}t^{-1})$ frequently reported [24] for plastic media, as well as high rates of application, found even in the study of super-rate roughing filters [20], are the evidence that biological processes must be preceded by a rapid physico-chemical mechanism.

The second mechanism — oxygen transfer limitation modelling is based on the well-known chemical engineering principle of increased mass transfer with increased turbulence.

Several authors have produced design models based on the oxygen limitation mechanism [15], taking into account the laminarity of the falling liquid film and, thus, laminar diffusion coefficients. The solutions of the initial second order, partial differential diffusion equation, frequently related BOD removal to the height of tower, its oxygenation capacity and oxygen diffusivity only. As shown by the author [18] such equations are in a very poor agreement with actual removals, and are not at all suitable for design purposes, where complex substrates of various wastewaters differ greatly from the pure substrates used to verify the theory.

The third model mechanistic approach — substrate transfer limitation — has utilized similar partial differential diffusion equations, and an assumption that several are constant. Several sophisticated solutions offered to the designers and researchers, [3], [4], have been analyzed by the author. It has been found [18], that most of them after certain rearrangement and manipulations may be presented in a familiar form

$$S_e/S_a = \exp\ (-Kt).$$

Another design approach offered by Maier et all. [14], was based on a pair of second order partial differential equations — one for diffusion in the liquid film, one for diffusion in the microbial slime. Similar approach taking account of two differential equations has been presented by Ames et all. [1]; but it also carries the same deficiencies.

All the models fail to recognize the importance of the organic load in biological systems. This approach may be correct from the standpoint of chemical engineering (unless such problems as poisoning of catalysts or diffusion limitation appear,) since concentration is the usual force. In biological systems, particularly when the substrate is soluble, the load may be of importance.

One of the major deficiencies is the assumption of heterogeneous, fixed film reaction. High recycle ratios, as applied in case of industrial wastes, provide conditions approaching homogeneity.

Assumption of laminarity for all filters is not sound since the flow, even in the random media filters, exhibits parameters characteristic of transient hydraulic regime ($Fr \leqslant 1.0$; $\mathrm{Re} \geqslant 4$–25). From the standpoint of mass transfer processes, rippled laminar flow such as that occurring in most biofilters may be considered as turbulent [21].

In conclusion of the above discussion of mechanistic equations it should become evident that at present there are no satisfactory models of the three-phase heterogeneous biological reactor, such as the trickling filter. The only solution remaining is to find out a model that would adequately correlate the experimental data and could be used for predictions of treatment efficiency in the field.

Such approach was evidenced by sanitary engineers in this country and abroad, where two types of empirical models are in use. One type relates the variables by dimensional analysis and/or statistical regression technique. Another approach is based on statistical curve fitting of constants in the conventional equation given by Velz or Eckenfelder. The most popular, beside the Eckenfelder's model, is the Galler and Gotaas model derived statistically, and as proved by experimental data, valid only for a narrow range of concentrations in municipal sewage. Similar restrictions apply to the CUGW model used in Poland [2]:

$$S_e = S_0 \; 10^{-1.8H/Q^{0.75}}, \tag{3}$$

and to the purely empirical curve-fitted model by Rincke

The latter model is supposedly valid for a wide range of loads $L = 0.10-1.20$ kg $BOD_5/m^3 \cdot d$. Obvious errors will arise if the design engineer applies such models to industrial wastewaters which always differ in their BOD_5/BOD_u and BOD/COD ratios, i.e. in their biodegradability factors. Errors may also result if filter media used by the designer are other than the media employed in the model derivation. Full critique of these approaches, presented elsewhere [18], documents the fact that the design of trickling filters can be based solely on the results of full laboratory and pilot scals studies.

In conclusion, the parameters influencing the removal efficiency are not fully recognized. Of the three elements considered in the modelling: diffusion of substrate, diffusion limitation of oxygen, and limiting rate of biochemical oxidation — the oxygen limitation is the least likely rate determining step. Similarly, assumption of simplifications employed in other mechanistic models yields them unsuitable for design purposes. The flow regime in high-rate modern trickling filters is turbulent from the standpoint of mass transfer; the plastic media biofilters tend to follow first order kinetics without the transfer limitations. Of the numerous models tested the plug-flow model, proposed by Eckenfelder, yields fairly adequate results, provided that the design stage is preceded by laboratory studies.

4. THE DESIGN EQUATION

Experiments on high-rate tricling filters have been conducted in laboratory and full scale — as described elsewhere [18], [20]. The experiments were aimed at determining the optimum operational parameters for biofilters heavily loaded with strong pharmaceutical wastes whose composition changes due to the batch operation of the manufacturing plant. Initial analysis of results from these studies proved that all standard correlations, such as the first order, second order, and enzymatic kinetics, fail to approximate the data adequately. The best fit was obtained only after plotting the data in a semi-long scale of S_e versus $1/L$ (Fig. 1). The resulting equation is:

$$S_e/S_x = \exp(-K/L), \tag{4}$$

where K is the overall reaction rate coefficient $(ML^{-3}t^{-1})$, L is the total applied organic loading $(ML^{-3}t^{-1})$, and $S_x(ML^{-3})$ is the intersection with the S_e axis, usually equal to the mean value of S_a.

As will be demonstrated later on the basis of results of studies conducted by other researchers on various wastes, the curves S_e versus $1/L$, in certain cases, demonstrate a point of an abrupt charge of direction. This change is interpreted as a change of rate with which effluent concentration responds to varying loads. At low loadings this rate,

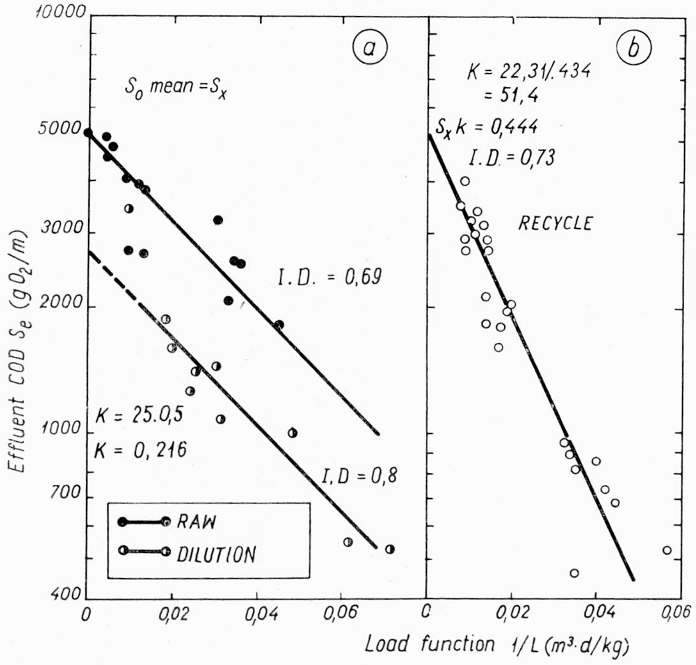

Fig. 1. Interpretation of data on pharmaceutical wastes treatment on Koroseal

Rys. 1. Interpretacja wyników oczyszczania na Korosealu ścieków z przemysłu farmaceutycznego

(denoted by K and found as a slope of the line in logarithmetic coordinates), is constant and may be found characteristically lower than for the same filter operated as a high-rate trickling filter.

It must be stressed here that K is by no means similar to the treatability coefficient, as regarded by some authors using classical concepts of more and less "treatable" or degrable wastes. It is a proportionality coefficient relating applied organic loading to effluent concentration and as such it is expressed in units of (M/L^3t). Its magnitude depends as much on the magnitude of applied loading as on the quality of waste, and on its relative strength and ease with which an effluent concentration is effected.

For oriented plastic media K was found to be a simple function of specific surface area $A(L^2/L^3)$. Thus, it is possible for the same type of wastes and range of influent concentrations to find the true proportionality (removal coefficient) factor denoted by $k(M/L^2t)$:

$$k = K/A. \tag{5}$$

In the case of small fluctuations in the strength of the incoming wastes around S_a mean, the relationship developed may take the following form:

$$S_e/S_a = \exp(-K/L). \tag{6}$$

The model yields itself to comparison with the activated sludge organic loading design model. The volumetric load in the biofilter is defined here as:

$$L = (Q \cdot S_a)/H;\ (ML^{-3}t^{-1}) \tag{7}$$

and in case of activated sludge the load, i.e. food (F) to microorganisms (M) ratio is:

$$L = S_a/Xt;\ (MM^{-1}t^{-1}), \tag{8}$$

where X — is the mixed liquor volatile solids (ML^{-3}) and t — detention time.

For trickling filters the equation (7) will take the form:

$$F/M = (QS_a)/(AH);\ (ML^{-2}t); \tag{9}$$

or

$$F/M = L/A. \tag{10}$$

Since the developed form of the derived trickling filter equation (6) is:

$$S_e/S_x = \exp\ (-kAH/QS_a) \tag{11}$$

or, for constant influent concentration, where t is proportional to H/Q:

$$S_e/S_x = \exp\ (-kAt/S_a) \tag{12}$$

then the final form of the proposed trickling filter equation may be written as:

$$S_e S_x = \exp\ \big(-k/(F/M)\big). \tag{13}$$

Based on long-time research on trickling filters the temperature correction coefficient may be accepted as $\Theta = 1.025$. For industrial effluents, however, Θ values should be determined. With $\Delta T = T-20$; (°C) the full expanded form of the design equation is:

$$S_e/S_x = \exp\left(\frac{-k\Theta^{\Delta T}AH}{QS_a}\right), \tag{14}$$

where: S_x is the intercept with the y-axis, usually correspoding to the average value of S_0, sometimes to the average value of S_a; S_0 is the concentration of raw wastewaters S_a — mixed with recycled effluent, S_e:

$$S_a = (S_0+NS_e)/(1+N), \tag{15}$$

where N is the recyle ratio of the volume recycled to the volume of raw wastes.

It should be noted that L does not contain the exponent n on Q as in Equation 1. This differentiates the present approach from previous methods even further. Volumetric load, as such, is not related to the mean residence time, unless the concentration S_a is constant.

So far the problem with the coefficient n has been substantial. This can be explainded by the frequent discrepancy between results of hydraulic studies and the value of n obtained from the graphical technique, such as that proposed by Eckenfelder. Based on both hydraulic studies and the above mentioned graphical techniques n was found equal to 1.0 and 0.918, respectively, in this study. Generally, oriented, sheet-like media will have $n = 1$, while for random media n would approach 0.5 [21].

5. DISCUSSION OF THE MODEL

The design formula presented herein is substantiated elsewhere [21] as converging with other models, mechanistic or empirical in nature. The so-called substrate kinetics model introduced by GRAU [9] is easiely integrated into the form of equation (12). Mathematical manipulations and simplifications give the same result with the empirical formula for trickling filter design proposed by TUCEK, et all. [25], and by LAMB and OWENS [13], and with the well-known NRC design formula.

The CUGW design model is clearly a particular case of the model proposed in this paper. It is unfortunate that such models as the CUGW equation or Rincke's model tend to become standard design procedures. In fact, the applicability of such models is limited only to a very narrow range of concentrations and only to one particular kind of wastewaters (e.g. municipal sewage). The application of such models to any other type of wastewaters or to a different trickling filter media yields unexpected by the designer and often serious errors.

The most used empirical approach correlating the removal $(S_0-S_e)/S_0$ with the applied loading was popularized in Europe by Imhoff, Rincke, Ganczarczyk, and put in use by ICI — manufactures of Flocor. This graphical approach may be presented mathematically as:

$$(S_0-S_e)/S_0 = K/L. \tag{16}$$

Taking a Maclaurin series expansion of the equation (4):

$$S_e/S_0 = \exp(-K/L) = 1-K/L+(-K^1/L)^2/2+ \dots \tag{17}$$

one can obtain, for small values of K/L, the reduced form:

$$S_e/S_0 = 1-K/L. \tag{18}$$

For large organic loadings L, this form is identical with equation (16), further proving the applicability of first order kinetics to heavily loaded filters.

The applicability of the expanded form of the proposed formula may only be demonstrated by analysing data from various filter media, operated at varying loads, but with identical initial substrate input. Such data has been extracted from the studies at WRC laboratories at Stevenage [5] on six parallel biofilters; the data yielded exceedingly well to the $S_e/S = \exp(-K/L)$ and $K = kA$ correlations. Similarly the parallel studies of JOSLIN [11], on two types of sewage proved the proposed equation to be well equipped to handle the problems of ponding and biomass bridging on the media. Figure 2 presents the removal data from Stevenage studies, while Figure 4a presents the correlations of $K = kA$. Figure 3 presents Joslin's data for two townships — Derby and Cheltenham.

Derby sewage was much stronger and contained a high proportion of industrial effluents having appreciable soluble COD and minimal suspended solids, whereas Cheltenham sewage was an average sewage primarily of domestic origin. The filters were operated without recirculation. It must be noted that, due to the continuously changing composition of the soluble and suspended matter, sewage is a very poor experimental waste,

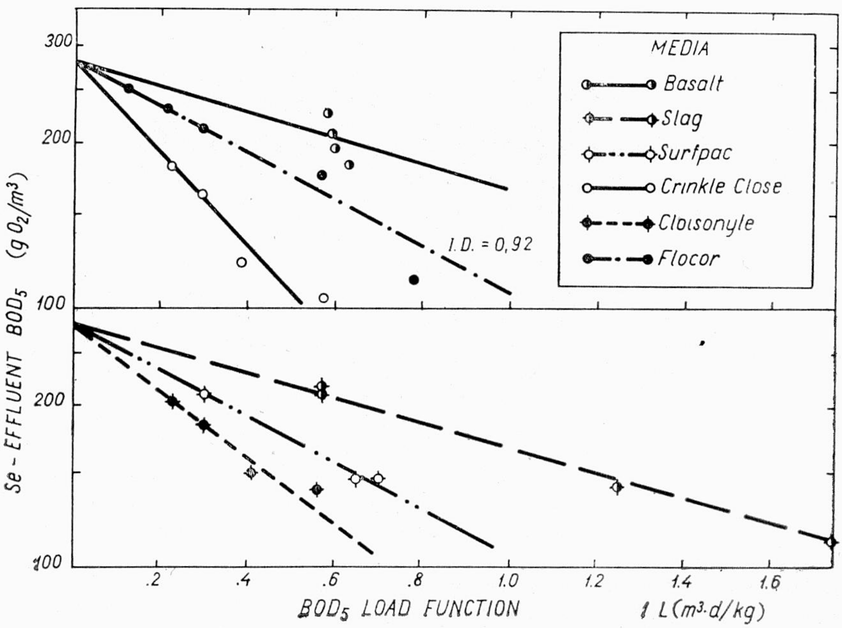

Fig. 2. Municipal wastewater treatment on parallel biofilters $S_a = 280 g/m^3 - BOD_5$

Rys. 2. Oczyszczanie ścieków miejskich na równoległych bio ltrach $S_a = 280 g/m^3 - BZT_5$

and the results obtained were hardly under controlled conditions. Also, the actual specific surface area $A(m^2/m^3)$ of Crinkle Close Surpac is the average of $(161+148)/2 = 154$, as the data illustrated 2 filters with different depths and different ratios of Surfpac/Flocor packing in Cheltenham.

Figure 4b proves that certain high surface area media, like the Crinkle Close Surfpac ($A = 160\ m^2\ m^3$) become coated by slime and exhibit a much smaller active surface area than quoted by the manufacturer.

As the slopes of the lines, prior to and past the inflection points, are plotted against the respective specific surface areas for data in Fig. 3, further insight into the proposed method is possible. For high rate trickling filters specific surface is directly related to the slope K as proposed in equation $K = kA$. The proportionality coefficients for the first

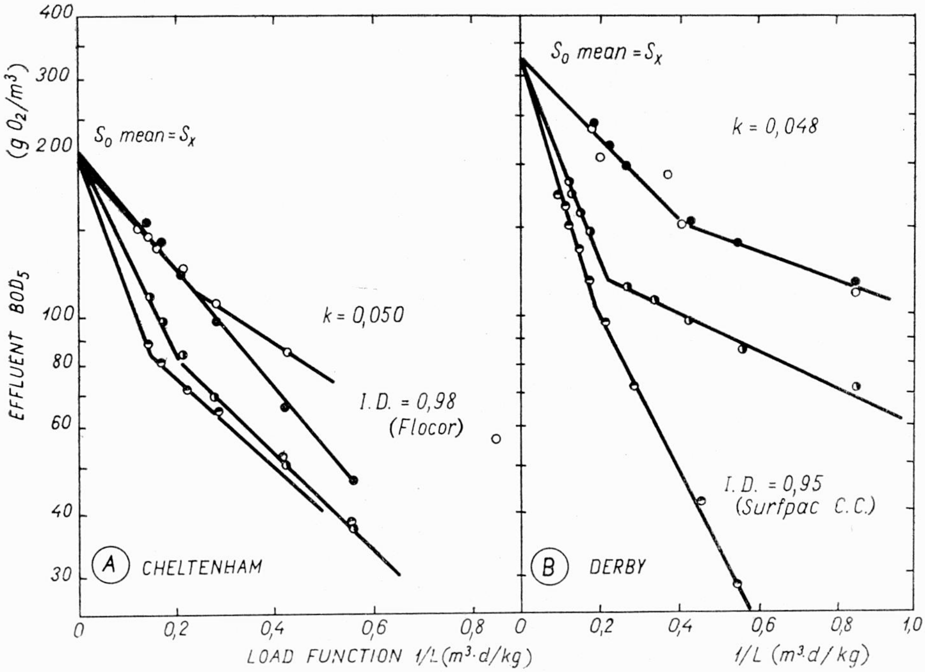

Fig. 3. Parallel biotreatment of municipal wastes on different media

◑ — 6′′ slag, ◑ — 4′′ slag, ○ — flocor, ● — surfpac C.C. T°C ≠ const; S_0 mean = S_x

Rys. 3. Biooczyszczanie ścieków miejskich na różnych wypełnieniach w równoległym układzie

limbs of the curves are $k_{1,} = 0.048$ kg/m²d for Derby, $k_{1,} = 0.050$ kg/m²d for Cheltenham and $k = 0.0104$ kg/m²d for Bruce and Merkens data.

At high loadings specific surface area of Crinkle Close Surfpac is apparently smaller than quoted by the manufacturer. The high A(4 inch slag) media in Figure 4b showed severe ponding.

Data for several industrial effluents treated on various plastic media have also been successfully analyzed by this method. Very good correlation was obtained on the data reported by Gańczarczyk [8] for a rolling tube model of a planar-type trickling filter. Figure 5 presents the data for both the BOD_5 and the permanganate oxygen demand (or value — PV). In all the cases the lines evidence a distinct inflection indicating two different rates of pollutants removal at various ranges of pollutant load function. Since the value of A has not been reported by Gańczarczyk, a modified load function had to be used — A/L.

Similar inflection point has been found for the data reported by Audoin on the Cloisonylle media (Figure 6), where varying heights were used [21]. It appears that depth is again just one parameter in $L = H/Q \cdot S_a$ and that effluent quality is related directly to the volumetric load.

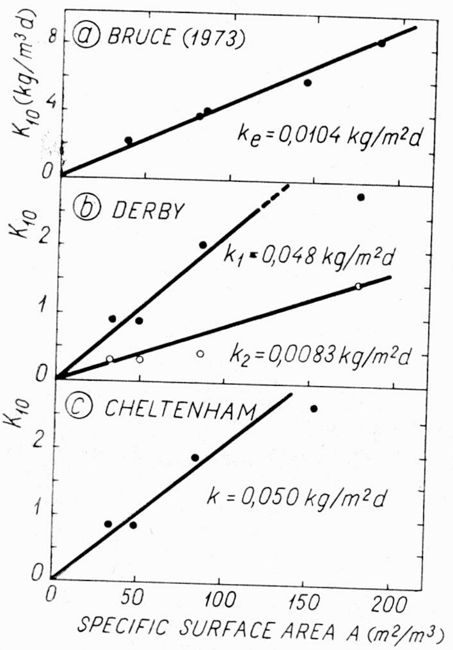

Fig. 4. Determination of k

Rys. 4. Wyznaczanie k

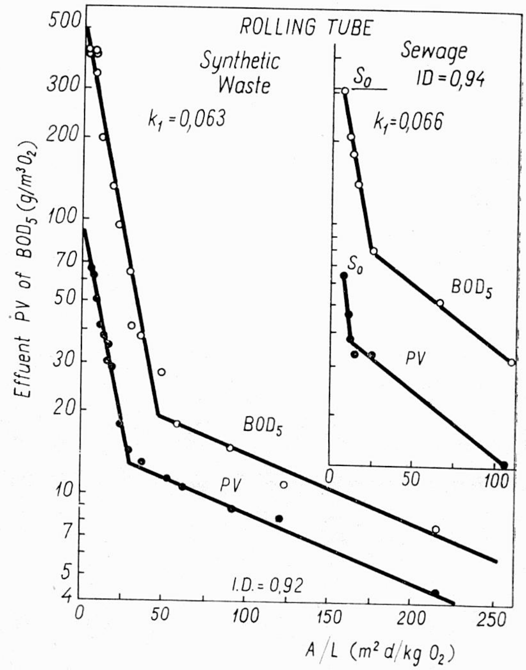

Fig. 5. Interpretation of Gańczarczyk's pilot data

Rys. 5. Interpretacja wyników Gańczarczyka otrzymanych w skali półprzemysłowej

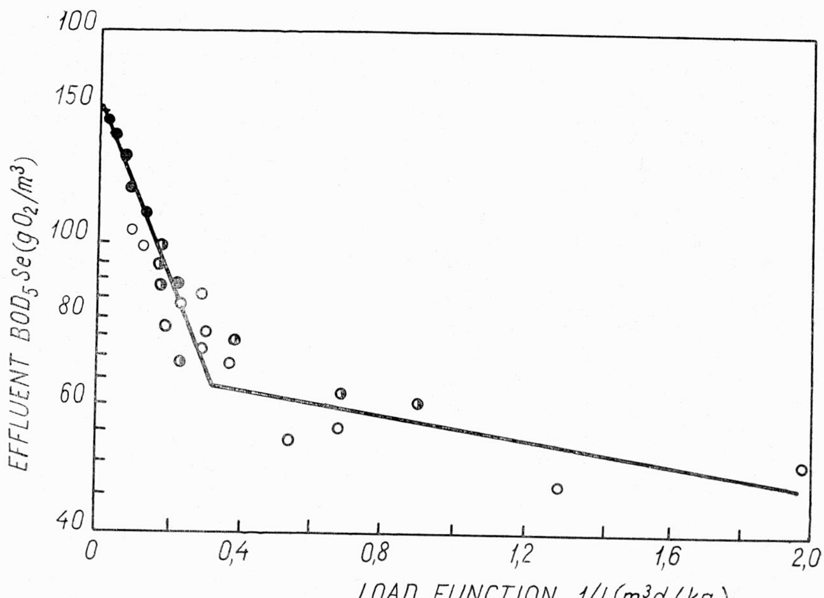

Fig. 6. Treatment data for varying depths of Cloisonylle media

sewage: $K = 0.186$; I.D. = 0.76; media depths (H) ● –2 m, o –4 m, ◑ –6 m

Rys. 6. Wyniki oczyszczania dla różnych głębokości wypełnienia Cloisonylle

$K = 0.186$; I.D = 0.76; wysokość (H) – ● – 2m, o – 4m, ◑ 6 m

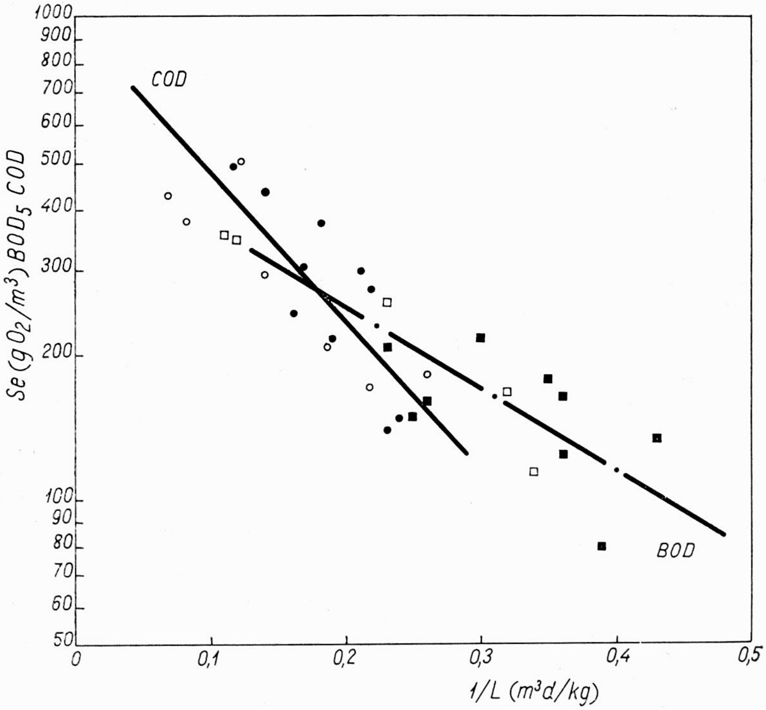

Fig. 7. Combined municipal industrial wastes treatment on experimental screen media
● –25% COD, o–75% COD, ■–25% BOD, □–75% BOD

Rys. 7. Oczyszczanie ścieków miejsko-przemysłowych na złożu siatkowym

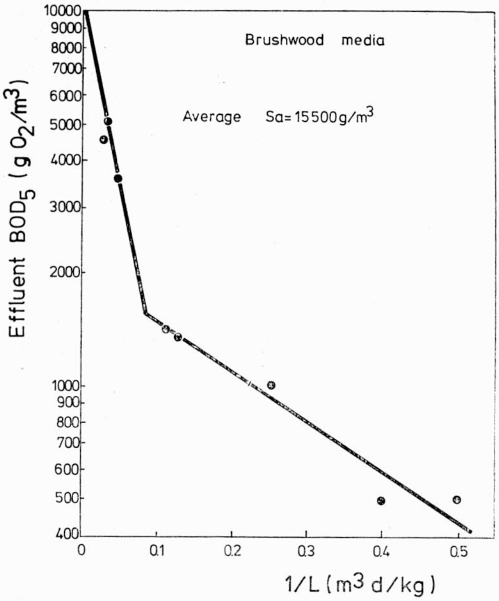

Fig. 8. Piggery manure treatment on experimental brushwood media biofilter

Rys. 8. Oczyszczanie gnojowicy świńskiej na złożu faszynowym

Figure 7 illustrates data extracted from recent work conducted at the Environmental Development Institute on treatment of a mixture of industrial effluents with sewage on an experimental hanging plastic screen-bags media. Although the medium seems to have poor ventillation and slime distribution properties and is far from being uniform and oriented, fair removal results were obtained.

Further examples of such correlations have been attained recently for various wastes, such as fruit and vegetables effluents, kraft wastes, hardboard effluents and other effluents from the timber industry. Figure 8 presents interpretation of data obtained by British researchers on piggery manure treatment on experimental natural brushwood media.

6. BIOFILTERS DESIGN RECOMMENDATIONS

The design procedures that follow are based on one basic assumption, that the design of the trickling filter today can only be based on extensive laboratory and/or pilot-scale studies. This is particularly true for industrial wastewaters and for trickling filters operated under high or super-high organic loadings [20]. It has to be stressed, once again, that the designer commits a serious error assuming that standard literature derived coefficients and removal efficiencies are valid for his particular installation. As evidenced by the inflection of curves in some of the graphs the trickling filter responds differently to organic loading in different ranges of L (kg/m^{3}d). This inflection point (if it exists for particular media, type of wastewaters, etc.) has to be located so that the designer can specify the range of load variations that will not affect the removal efficiency. For example, in Figure 6, the load variations between 0.5 and approximately 2.85 kg BOD_5/m^{3}d bring about a relatively small change in effluent BOD_5 from 46 to 65 g O_2/m^3, due to the low value of the rate coefficient k_2. At the same time the load change from. 3.1 to 5 kg BOD_5/m^{3}d yields a large change in effluent BOD_5 — from 68 to approximately 95 g O_2/m^3. As suggested by mechanistic approach to the theory of substrate removal the sudden change is the result of domination of particular processes — presumably physico-chemical and biological in nature — over the slower processes — presumably biochemical at lower loadings.

The studies conducted for design purposes should take account of the following criteria:

a) the laboratory microtower should be packed with the same media that will be used in the full scale installation;

b) under no conditions should the results from the oriented type planar media, used in the pilot studies, be extrapolated to a full scale installation packed with random media;

c) winter and summer conditions should be simulated by proper temperature control. Studies may be conducted at laboratory room temperature but the wastewater temperature should be controlled by refrigeration or heating tapes (it is preferable to simulate winter conditions by running the tests outside the laboratory facilities, as long as the scale-down of lab-units will not distort the actual temperature response of the full scale towers);

d) the wastewater should be fully equalized and pretreated with proper pH and nutrient content adjusted;

e) the dimension of depth H of the tower, cannot be distorted by modelling.

It is of paramount importance to investigate the full range of organic and hydraulic conditions, with the recirculation ratio varying between 0 and 500%. The increasing recycle brings the biofilter closer to the activated sludge principle (i.e. the heterogeneous reactor becomes pseudo-homogeneous).

The design steps may be summarized as follows (Fig. 9):

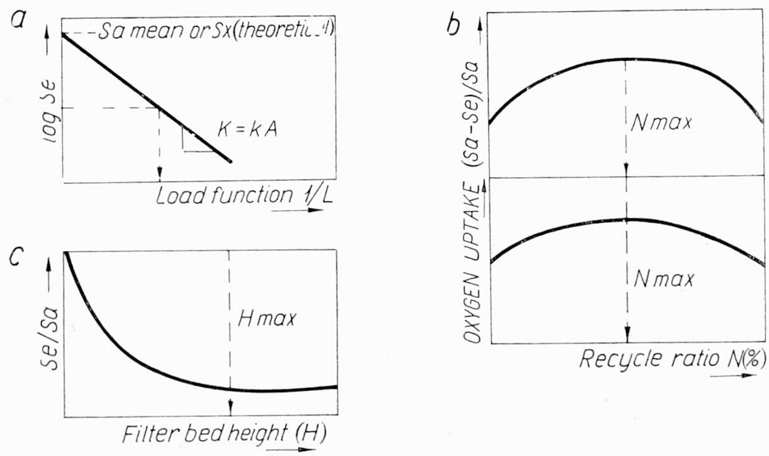

Fig. 9. Basic biofilter design steps

a) determination of the maximum loading

b) determination of the optimum recycle ratio

c) determination of the maximum heigh

Rys. 9. Podstawowe etapy projektowania złoża biologicznego

1. Determine the limiting load from the standard arithmetic correlation of the load applied versus load removed (if such a load exists for the given set of data).

2. Find the maximum load corresponding to the desired effluent quality S_e (Fig. 9a). In certain cases of little recycle practiced — or homogeneous in nature wastewaters — a straight line is obtained — an intersection with the y-axis is equal then to the mean value of S_a. If an inflection point is obtained then the intercept may become a theoretical value denoted as S_x. Both rate coefficients should then be calculated and used in designing the filter.

3. Find the optimum recirculation ratio of $Q_{recycled}/Q_{raw}$ from the graphs in Fig. 9b. Examples of such correlations are given elsewhere [20], [21].

4. Determine the maximum filter height from the graph similar to Fig. 9c.

5. Find the optimum depth by performing an optimization analysis with the variables: S_e, H, L_{max}, N_{opt}.

The following criteria are recommended here:

a) graph of S_e/S_a versus depth;

b) trends in depth selection for the given type of wastewater, influent strength, S_a, and type of media used;

c) geometrical similarity to the total depth, H, used during the pilot studies;

d) economic analysis of the pumping head (H+losses) versus the cost of available area and volume of flow, q(m^3/d).

6. Apply scale-up multiplication factors to depth, H, and filter media volume, V, in order to account for channeling and uneven distribution of biological slime and the resulting decrease in active specific surface area.

7. Introduce necessary corrections for the low-temperature periods and for the accepted raw wastewater influent variability.

7. DISCUSSION

Plastic media trickling filters have one more advantage over the conventional media, namely, they do not require the primary sedimentation tanks — provided that the influent is well screened and will pass the distributors. Generally, however, the biological wastewater treatment system works better with the primary clarifiers in place and thus, unless the roughing treatment is required, designers put them in.

A typical biofilter installation will consist of screens, primary clarifiers, two biofilter towers in series and a final clarifier. Intensive recycle is practiced. Characteristically, there are no intermediate clarifiers between the stages. As many as six stages in series have been used, yielding a total height of 36–40 m. It is doubtful if such series operation is economically feasible (6 separate pumping units) — and whether such approximation of the ideal plug flow mechanism allows the plant operator the flexibility of changing the biofilter technological parameters. It is much easier and more economical to operate a series of two to a maximum of four trickling filters in series and practice intensive recirculation.

The design hints for plastic media biofilters are presented elsewhere [19]. The PVC media used in USA and Great Britain is sold in blocks $0.6\times0.6\times1.0$ m; the media developed in Poland have similar block dimensions. The media are available in standard, heavy, and extra heavy duty finish costing anywhere from 70 to 100 dollars/m^3. The combination of the media with various strength allows to design the maximum height of trickling filters from 8–15 m, without the intermediate supports (in case of oriented plastic media).

The use of block media permits a greater flexibility in shape-design of the towers. The most popular are octagonal or square (in cross-section) towers irrigated with fixed nozzle sprinklers. Figure 10 presents rectangular design biofilters — in series, while Figure 11 shows a cross-section through a circular trickling filter with rotary distributor.

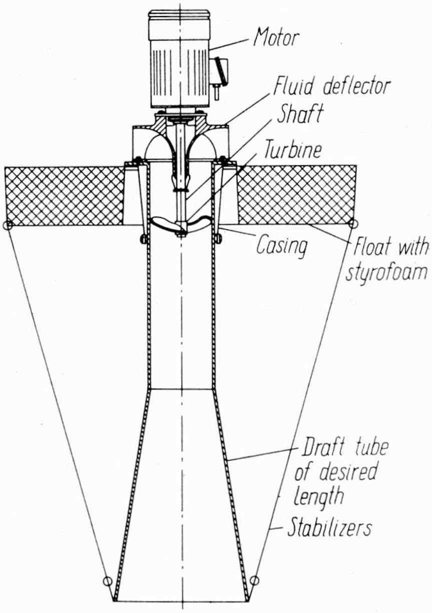

Fig. 10. Plastic media installation for treatment of pharmaceutical wastes

Rys. 10. Złoże biologiczne oczyszczające ścieki z przemysłu farmaceutycznego

The plastic media trickling filters are well suited for reception of very high organic and hydraulic loadings. The media, however, are not limited to roughing or primary treatment applications only. The use of this media in fining treatment has been reported. At very low organic loadings, below 0.10 kg BOD_5/m^3d nitrification has frequently been attained with soluble industrial wastes (slaughter houses, yeast plants).

In summary, the modern trickling filter packed with plastic media has been successfully applied to a variety of industrial effluents, ranging from strong animal feedlot effluents, dairy, brewery and distillery wastes to pulp and paper and food processing industrial

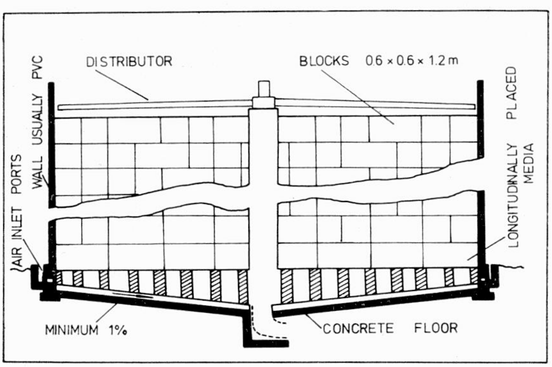

Fig. 11. Cross-section of an plastic media oriented circular biofilter

Rys. 11. Przekrój złoża biologicznego z wypełnieniem ztworzyw sztucznych wastewater. The removal efficiencies attained ranged from 60 to 97% of BOD_5 removal, the higher removals corresponded to multistage plants with recycle and careful operation. The volumetric loads applied usually ranged from 0.3 to 5 kg BOD_5/m^3d; the influent BOD_5 concentration ranged from 180–3000 g/m^3. For roughing pretreatment loads exceeding 16 kg BOD_5/m^3d have been used. There seems to be no upper limit on the flow-through capacity of the plants with trickling filters. The plastic media have been applied in individual household applications (e.g. Aquatair) and in plants of capacity approaching 100 000 m^3/d and more.

Thus, the plastic media trickling filter is becoming strongly competitive with the activated sludge, even more so as it requires less land for given BOD_5 removal, less energy per weight of removed pollutant and creates less maintenance problems than activated sludge. It has also been demonstrated that in certain cases where activated sludge cannot be applied due to, for example, bulking problems inherent with such wastes as potato or yeast effluents, only the trickling filter can provide adequate treatment. The sludge produced from hydraulically well loaded oriented plastic media filters usually evidences much better settling and dewatering characteristics than excess activated sludge.

8. SUMMARY AND CONCLUSIONS

Design procedure presented have been based on the newly derived first order substrate removal kinetic model:

$$S_e/S_a = \exp(-k^{\Delta T}_{\Theta AH/QS_a}). \tag{14}$$

The model uses laboratory or pilot scale data for derivation of the constant $K = kA$ and determination of the response of effluent quality to the changes in the incoming volumetric load, at given temperature. Due to the specifics of heterogeneous biological reactors it is very risky to accept k values derived from literature. It is concluded that the designer can use literature k values only in case of identical wastes, treated on the same type of filter media and in the same environmental conditions (pH, nutriens, S_a variablity, etc).

It has been documented that the intuitive correlations of BOD removal versus load and several popular empirical equations can all be derived by the simplification of the proposed design model. The risk of serious error awaiting designers that use empirical models for various kinds of effluents has been demonstrated.

In certain instances the graphical correlation of (log S_e) versus ($1/L$) shows sudden inflection. This is interpreted as the change in the complex physical, chemical and biological characteristics of treated wastewaters with increasing recirculation of filter effluent. The high value of k_1 indicates rapid improvement in effluent quality with incremental decrease of organic loading — and unstable operation of the filter. The lower value of k_2 (lower limb of the curve below the inflection point) indicates a more desirable steady-state operation.

The equation proposed discredits the popular tendency to increase the height of the filters. Height of the filter is only one of the elements that influence pollutant removal and can be compensated for with increased recycle.

Recirculation is found to be the most fundamental variable allowing a proper control of such filter variables as: raw waste strength variability, ponding and development of anaerobiosis, shock-load and toxic load recovery, proper slime unloading and proper hydraulic regime on the slime.

The scale-up from laboratory studies should account for: the decrease of specific surface area due to slime bridging, the uneven liquid distribution over the entire filter, the uneven slime mass transfer and contact opportunity, the annual temperature variability and the variability of strength and volume of raw wastewaters.

PROJEKTOWANIE ZŁÓŻ BIOLOGICZNYCH NA PODSTAWIE WYNIKÓW BADAŃ

Na podstawie wyników badań wyprowadzono nowy model do projektowania złóż biologicznych. Model został sprawdzony na wynikach badań różnych rodzajów ścieków i wypełnień złóż, opisanych w literaturze. Model, korelując efekt oczyszczania $S_e/S_a = \exp(-K/L)$, nadaje się szczególnie do projektowania wysoko obciążonych złóż z wypełnieniem plastykowym. Udowodniono, że model z powodzeniem zastępuje tradycyjne wzory Imhoffa, Rinckégo, Gallera i Gotaasa lub inne modele empiryczne stosowane najczęściej dla wąskiego zakresu parametrów pracy złoża.

Podano szczegółową metodykę projektowania, wychodząc z założenia, że praktycznie wszystkie złoża powinny być projektowane na podstawie wyników badań laboratoryjnych lub pilotowych, zwłaszcza jeśli chce się uzyskać efekt oczyszczania zbliżony do efektu osadu czynnego. Omówiono dotychczasowe próby wyprowadzenia podstawowego równania opisującego procesy zachodzące w złożu biologicznymi

PROJEKTIERUNG BIOLOGISCHER KÖRPER ANHAND DER FORSCHUNGSERGEBNISSEN

In Anlehnung an die letzten Forschungsergebnisse wurde ein neuer Model zur Projektierung biologischer Körper eingeführt. Dieser wird nach Forschungsergebnissen verschiedener Abwasserarten und Hinterfüllung der Lagerstätte, die in der Literatur beschrieben wurden, nachgeprüft. Der Model, in Korelation des Reinigungeffektes $S_e/S_a = \exp(-K/L)$ findet besonders seine Anwendung bei Projektierung der stark belasteten Lagerstätte mit Plasterhinterfüllung.

Es ist nachgewiesen worden, dass der Model sich ausserordentlich als Ersetzung der traditionellen Formel Imhoffs, Rinckes, Gallers und Gotaas und für empirische, am häufig wichtige für geringen Parameterbereich der Lagerstätte, eignet.

Von dem Prinzip ausgehend, wurde eine gründliche Projektierungsmethodik angegeben. Alle Lagerstätte sollen praktisch anhand der Labor- und Pilotforschungen projektiert werden, besonders wenn man ein Stabilitätsgarantie des Reinigung effektes ähnlich dem Belebtschlam erreichen will.

Ausserdem wurden die bisherigen Versuche hinsichtlich der Einführung der Prozessgleichung, die im biologichen Körper auftritt, zur Erörterung gebracht.

ПРОЕКТИРОВАНИЕ БИОФИЛЬТРОВ ПО РЕЗУЛЬТАТАМ ИССЛЕДОВАНИЙ

На основе результатов исследований выведена новая модель для проектирования биофильтров, проверенная затем по результатам исследования различных видов сточных вод и заполнений фильтров, описанного в научной литературе. Модель, в которой соотносится эффект очистки $S_a/S_e = \exp(-K/L)$, особенно пригодна при проектировании высоконагруженных фильтров с пластмассовым заполнением. Показано, что модель успешно замещает традиционные формулы Имгоффа, Ринке, Галлер и Готаса, а также другие эмпирические модели, справедливые, чаще всего, для весьма узкого интервала параметров работы биофильтра.

Приведена детальная методика проектирования, причем принято положение, в соответствии с которым все биофильтры должны проектироваться на основе лабораторных исследований или полузаводских экспериментов, особенно, если желательно получить гарантию постоянства эффекта очистки, близкого к активному осадку. Кроме того, обсуждаются проведенные до настоящего времени опыты по выводу основного уравнения процессов, преобладающих в биофильтре.

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