

M. BECCARI*, A. ROZZI**

ANALYSIS OF RATIONAL APPROACHES FOR TRICKLING FILTER DESIGN

This paper analyses the main semi-empirical models for trickling filter design to be found in the current state of the art. Modifications to such models are proposed in order to obtain a closer correspondence to the true dynamics of the systems they represent. Lastly, this paper develops a new model for multicomponent substrate and draws attention to its close agreement with data from particularly reliable literature.

NOMENCLATURE

- A — filter cross sectional area (L^2),
- d — thickness of the active biological layer (L),
- E — residence time distribution (T^{-1}),
- H — filter depth (L),
- k — kinetic coefficient (T^{-1}),
- K — gross removal coefficient (M/L^3T),
- K_s — saturation coefficient (M/L^3),
- L^s — volumetric organic loading applied (M/L^3T),
- Q — hydraulic flow rate (L^3/T),
- s — specific surface area of the media (L^2/L^3),
- S — substrate concentration (M/L^3),
- S_a — influent mixed applied concentration (M/L^3),
- S_e — effluent concentration (M/L^3),
- S_0 — influent raw wastes concentration (M/L^3),
- t — time (T),
- t^* — mean residence time (T),
- u — liquid film velocity in direction z (L/T),
- V — filter volume (L^3),
- X — concentration of organisms in the biological film (M/L^3),
- z — axial coordinate (L),
- Y — yield (mass cells produced/mass substrate removed),
- μ_{max} — maximal specific growth rate (T^{-1}).

* Physical Chemistry Institute, University of Rome, 00100, Italy.

** Water Research Institute, CNR, Via F. De Blasio, 70123 Bari, Italy.

1. INTRODUCTION

The current preference for activated sludge processes instead of trickling filters does not appear to be sufficiently justifiable. Despite some undeniable advantages (slightly higher BOD_5 removal, lower plant costs, fewer problems from flies and odors), activated sludge processes also have some disadvantages with respect to trickling filters (e.g. higher operating costs, higher biomass sensitivity to operating shut-down as well as a requirement for more skilled management and the need to prevent bulking phenomenon).

One of the strongest arguments in favour of activated sludge processes is the better correlation between the design computations and the full scale results. On the other hand, despite numerous attempts, no model for trickling filter design has yet proved to be reliable.

It may be worth noting that a reliable model is expressed by means of a relationship in which the substrate removal is correctly correlated to the hydraulic and organic loadings of the influent and to packing and filter configurations. Certain coefficients appear in such relationships and their values must necessarily be determined by lab or pilot scale data, due to the fact that these coefficients depend on both the very nature of the substrate to be treated and the packing adopted.

Frequently in the past, the design of traditionally packed trickling filters was performed by means of empirical formulas obtained from data collected in plants operating in non-generalizable conditions. Among the more familiar formulas, we may recall those from the National Research Council [14] and from GALLER and GOTAAS [11]. A comparison of these formulas [18] reveals differences in packing bed volumes up to 1400% for the same conditions.

The definition of more suitable design relationships requires a consistent physical model to be selected as a reference.

The steps occurring in the overall process are the following: aeration of the raw waste (which flows either over or through the biomass film), transfer of the oxygen and of the substrate both through the raw waste and into the biomass, adsorption, substrate biochemical consumption and rediffusion of reaction products.

The reference physical model should take into account all the physical and biochemical factors involved in the process (*rigorous approach*). Equations obtained, [1], [2], [3], [24], [25], do not seem to be of much practical use in design as their solution requires the use of a digital computer and it therefore becomes difficult to understand the meaning of results. This approach also suffers from difficulties met in the determination of the various coefficients for the liquid film and biofilm. In addition, it should also be noted that a laminar hydraulic condition is usually assumed for this model (thereby facilitating balance equation solving). On the contrary, even at the rather low Reynolds numbers (10^1 – 10^2) that are typical of liquid films in trickling filters with oriented plastic media, flow conditions seem to be transitory or even turbulent [17]. In this case, solution of the mathematical model becomes even more complex.

The reference physical model should therefore be based upon assumptions that facilitate its use. This may be done in two ways:

— Overall process rate should be describable by considering biochemical process kinetics alone dealing with the other factors connected with mass transfer by means of empirical constants (*semi-empirical approach*).

— Transfer processes and biochemical reactions should be considered at the same time though the model be simplified somewhat (*semi-rigorous approach*). In this way PORTER [19] assumes that the resistance to mass transfer in gas and in liquid film is very small compared with that of the biomass. Process rate is therefore governed by the biochemical reaction and in biomass transfer.

When we adopt the *semi-rigorous approach*, design relationships are obtained that, even in the simplest of cases (zero order kinetics for the biochemical reaction; a choice of boundary conditions simplifying the integration of the differential equations that describe the process) are noticeably complex just the same and include terms that are not easily worked out.

Consequently, the *semi-empirical approach* would appear to be promising for derivation of relationships to be used for design.

2. SEMI-EMPIRICAL APPROACH: ANALYSIS OF MODELS

2.1. EULER MODELS

The integration of the substrate balance equation is carried out with a mobile coordinate system (integration with respect to time).

The models proposed by SCHULZE [20], BRUCE [5], [6], ECKENFELDER [8], [9] and OLESZKIEWICZ [16], [17] are of this kind and based more or less explicitly on the following assumptions:

— Trickling filters can be schematically shown as plug flow reactors, wherein the total mean residence time t^* is a function of filter and wastewater features.

— Liquid film and biofilm are homogeneous and contiguous (the concentration gradients of both substrate and oxygen are effectively zero throughout the liquid film thickness; velocity is constant in each point of liquid film; microorganism concentration is constant inside the biofilm; the substrate degradation takes place at liquid film-biofilm interface). Alternatively, we can assume that the reaction takes place inside the biofilm, and the substrate and oxygen concentrations are constant throughout the biofilm thickness.

— Biomass features (nature, concentration, etc.) are constant throughout filter length (this is equivalent to using mean reaction coefficients that take into account the effective heterogeneity of the bacterial population).

The above-mentioned models differ from one another in their kinetic equation and in their empirical relationships which enable t^* to be calculated. Relationships of the form: $S_e/S_0 = f(t^*)$ are obtained. Some of the most familiar of these relationships are listed in the table for filters operated without recycle. Recirculation implicates a whole series of factors, some of which act favourably while others are detrimental to removal efficiency

* See alphabetically ordered index at beginning of paper for nomenclature meanings.

[15]. Recirculation therefore modifies such relationships more than is evident from the mass balance relationship existing between S_0 and S_a . The effects of recycle will be more closely investigated in a subsequent work.

Residence times are from 20 to 60 minutes for low-rate filters and as low as 2 to 10 minutes for high-rate filters. These values are much lower than those normally found in activated sludge process. As trickling filter biomass and activated sludges are qualitati-

Semi-empirical relationships for trickling filters operated without recycle
Półempiryczne modele złóż biologicznych bez recyrkulacji

Source	Kinetic equation	Mean residence time	Substrate removal
SCHULZE	$-\frac{dS}{dt} = kS$	$t^* = \frac{CH}{(Q/A)^a}$	$\frac{S_e}{S_0} = e^{-\frac{KH}{(Q/A)^a}}$ where $K = kC$
BRUCE	$-\frac{dS}{dt} = kS$	$t^* = \frac{C's^b}{(Q/V)^c}$	$\frac{S_e}{S_0} = e^{-\frac{K's^b}{(Q/V)^c}}$ where $K' = kC'$
ECKENFELDER	$-\frac{dS}{dt} = kXS$	$t^* = \frac{E's^p H}{(Q/A)^n}$	$\frac{S_e}{S_0} = e^{-\frac{\overline{K}s^p + pH}{(Q/A)^n}}$
		$t^* = \frac{E''H^{1-m}}{(Q/A)^n}$	$\frac{S_e}{S_0} = e^{-\frac{\overline{K}'sH^{1-m}}{(Q/A)^n}}$
			where: $X = Es$; $\overline{K} = kEE'$; $\overline{K}' = kEE''$
	$-\frac{dS}{dt} = kXS^2$	$t^* = \frac{E's^p H}{(Q/A)^n}$	$\frac{S_e}{S_0} = \frac{1}{1 + \frac{\overline{K}s^p - pH}{(Q/A)^n}}$
		$t^* = \frac{E''H^{1-m}}{(Q/A)^n}$	$\frac{S_e}{S_0} = \frac{1}{1 + \frac{\overline{K}'sH^{1-m}}{(Q/A)^n}}$
			where: $X = E_s$; $\overline{K} = kEE'S_0$; $\overline{K}' = kEE''S$
OLESZKIEWICZ**	$-\frac{dS}{dt} = kX\left(\frac{S}{S_0}\right)^{n***}$ with $n = 1$	$t^* = \frac{C''H}{Q/A}$	$\frac{S_e}{S_0} = e^{-\frac{K''s}{L}}$ where: $X = E_s$; $L = QS_0/AH$; $K'' = kEC''$

** — referring to high-rate trickling filters with oriented plastic media.

*** — kinetic equation as proposed by Grau et al. [12].

vely similar, we must suppose that a large stock of organic material is accumulated locally during passage through the filter. This is probably due to flocculation and adsorption mechanisms characterized by high rate kinetics. Subsequently, the accumulated organic materials are bio-oxidized at rates comparables to those of suspended biomass aerobic systems.

Consequently the K parameter in semi-empirical model kinetic equations (see table) cannot be rigorously defined as a kinetic coefficient, where the concentration X of the active mass is not explicitly set forth.

It should be noted that the schematic fluidynamic representation of the above-mentioned models (i.e. a filter as a plug flow reactor, corresponding to an infinite number of completely mixed reactors in series) is disproven by experimental evidence. Figure 1 shows the normalized pattern of residence times found by the authors in a trickling filter with Flocor packing as revealed by an added tracer (NaCl). A characteristic "tail" may be noted for extended residence times.

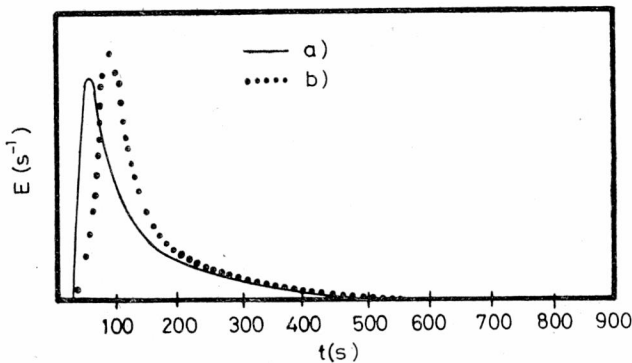


Fig. 1. Normalized pattern of residence times:

a) experimental pattern obtained in a trickling filter with Flocor packing (tracer NaCl); b) pattern obtained by computerized simulation

Rys. 1. Znormalizowany model czasów przebywania:

a) model eksperymentalny otrzymany w złożu biologicznym z wypełnieniem Flocor (tracer NaCl); b) model otrzymany przez skomputeryzowaną symulację

A similar tail was also found in other studies where other low concentration tracers (rodamine or radioactive tracers) were used.

The introduction of an axial dispersion coefficient into the plug model or the assumption that a filter consists of a series of completely mixed reactors enables us to obtain residence time distributions that are much more symmetrical than the experimental curves. Distribution curves quite similar to the experimental ones (fig. 1) were obtained by computerized

simulation making use of a filter model represented schematically as shown in fig. 2, where a series of completely mixed reactors are connected to other completely mixed reactors, but which are defined as "stagnant" due to their having longer residence times.

An improvement in the reliability of Euler models can moreover be obtained by evaluating the influence of residence time distribution $F(t)$ in the reactor on reaction kinetics.

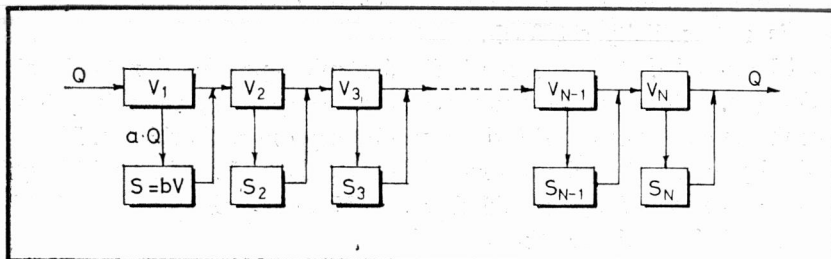


Fig. 2. Schema of trickling filter according to the stagnant reactors model ($a = 0.1$, $b = 0.6$)

Rys. 2. Schemat złoża biologicznego według modelu reaktorów stagnacyjnych ($a = 0,1$, $b = 0,6$)

In this case, relationship $S/S_0 = f(t)$ can be applied to flow percentage $E(t)dt$ that stays in the reactor for a time from t to $(t + dt)$. Removal can therefore be computed from the expression:

$$S_e/S_0 = \int_0^{\infty} f(t) E(t) dt \quad (1)$$

equal to the removal to be obtained when the models are applied in their original formulation ($S_e/S_0 = f(t)$) only if the following relationship holds true:

$$\int_0^{\infty} f(t) E(t) dt = f\left(\int_0^{\infty} E(t) t dt\right) \quad (2)$$

The relationship (2) is verified with zero order kinetics, while, for first order kinetics, we have:

$$\int_0^{\infty} f(t) E(t) dt > f\left(\int_0^{\infty} E(t) t dt\right) \quad (3)$$

where $f(t) = e^{-kt}$.

The value of the inequality in (3) is a function of both the numerical value of k and the particular model used.

Figure 3 shows substrate removal patterns as a function of k and proves that when the fig. 2 model is adopted, inequality (3) increases.

In conclusion, the approach suggested by the authors refers to a more accurate schematic representation of trickling filter hydraulics.

By using residence time distribution we obtain conservative solutions (especially for high values of k), but that seems to lead to some prospects for a better modelling of trickling filters.

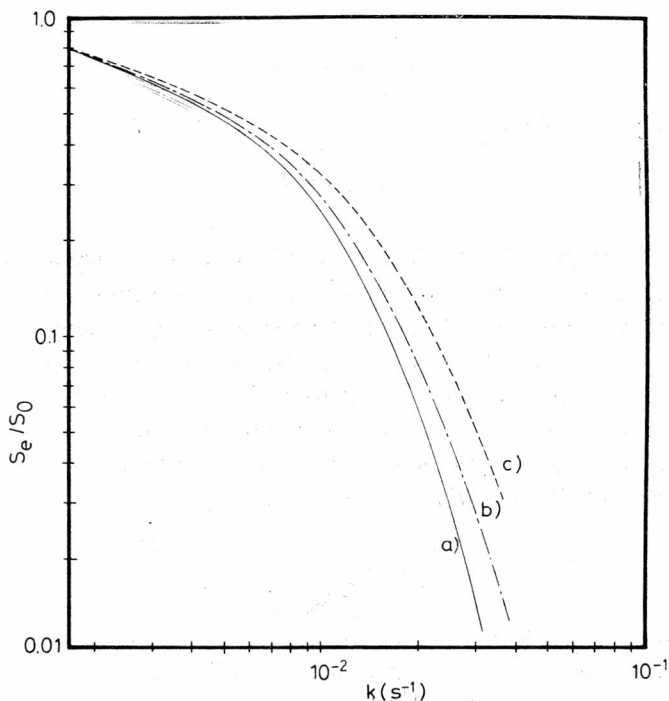


Fig. 3. Substrate removal vs. kinetic coefficients:

a) when the mean residence time is adopted; b) when (1) is assumed together with the model with seven completely mixed reactors in series; c) when (1) is assumed together with stagnant reactors model (7+7 reactors)

Rys. 3. Usuwanie substratu w zależności od współczynnika kinetycznego:

a) przy średnim czasie przebywania; b) przy założeniu (1) łącznie z modelem z siedmioma kompletnie zmieszanyymi reaktorami połączonymi szeregowo; c) przy założeniu (1) łącznie z modelem stagnacyjnych reaktorów (7+7 reaktorów)

2.2. LAGRANGE MODELS

The substrate balance equation is integrated by means of a fixed coordinate system (integration with respect to bed height).

The hypotheses relating to this model are substantially the same as those used for Euler models.

The mass balance equation for an infinitesimal filter volume dV is as follows:

$$u \frac{dS}{dz} = f(S, z).$$

VELZ [23] relates substrate concentration at axial coordinate as follows:

$$\frac{dS}{dz} = -KS$$

which, when integrated, gives

$$\frac{S_e}{S_0} = e^{-KH}.$$

KORNEGAY and ANDREWS [13] maintain the validity of some hypotheses of the above-described Euler models (e.g. plug flow, homogeneous liquid film, constant in-filter concentration of microorganisms) and also make the following assumptions:

- the biomass is active only in part of the whole biofilm thickness;
- the specific growth rate is expressed using Monod's equation;
- the growth yield is constant throughout filter height.

As a consequence of these hypotheses, it may be stated that substrate removal can be computed by means of the following relationship:

$$1 + \frac{S_e}{S_0} + \frac{K_e}{S_0} \ln \frac{S_e}{S_0} = \frac{\mu_{\max} s d X A H}{Y Q S_0}, \quad (4)$$

where saturation constant K_s varies as a function of hydraulic load Q/A so that mass transfer resistances are also held in due consideration.

Kornegay—Andrews model has not been satisfactorily verified experimentally [15], [21].

If, on the other hand, we assume μ_{\max} to vary as a function of hydraulic load in compliance with the same law which correlates Sherwood's number to Reynolds's and Prandtl's numbers, i.e.:

$$\text{Sh} = C \text{Re}^\alpha \text{Pr}^\beta$$

then we have the following expression:

$$1 - \frac{S_e}{S_0} + \frac{K_e}{S_0} \ln \frac{S_0}{S_e} = \frac{KH}{S_0 Q^m}. \quad (5)$$

Figure 4 illustrates the close agreement between relationship (5) and experimental data obtained from various sources.

It is to be noted that, both in connection with the original Kornegay—Andrews model and in connection with equation (5) given by the authors, corrective factors depending on diffusional resistances within the films and/or at interfaces are directly introduced in Monod (or Michaelis—Menten) kinetics.

What is more, KORNEGAY and ANDREWS extrapolate $S_0 - S_e$ as a function of $\ln(S_0/S_e)$ for $S_0 = S_e$ in order to obtain $\mu_{\max} s dXA/Y$ graphically, regardless of the fact that this is neither mathematically nor physically correct ($S_e \rightarrow S_0$ when $Q \rightarrow \infty$ or $H \rightarrow 0$).

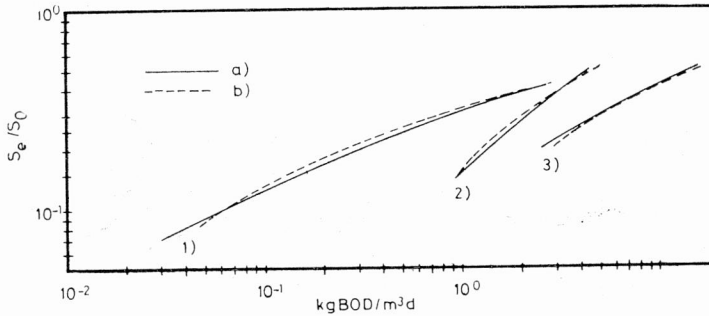


Fig. 4. Comparison between predictions: a) from (5) and experimental data; b) from various sources (1: [14]; 2: [22]; 3: [4])

Rys. 4. Porównanie pomiędzy przewidywaniami: a) z (5) i danymi eksperymentalnymi; b) z uznanych źródeł (1: [14]; 2: [22]; 3: [4])

3. MULTISUBSTRATE MODEL

A “delaying” effect on substrate removal kinetics seems to emerge from an examination of the literature-reported experimental data: the higher the initial substrate concentration, the greater the effect. The kinetic equations as proposed by GRAU et al. [12] and by FAIR et al. [10] explicitly contemplate such an effect.

The rationale for this influence of S_0 on biodegradation kinetics rests in the fact that when biomass contacts an already partially degraded solution of residual substrate concentration $S' < S_0$ (expressed as BOD_s or COD), it does not, in fact, interact with a solution that is more diluted than the original substrate, but reacts with a mixture of the original substrate (with $S'' < S'$ concentration) and its metabolites.

On the basis of this interpretation, we propose adopting a new model designed on the grounds of a multi-component substrate

$$S_0 = \sum_{i=1}^N S_{i0},$$

for each of which we have the following removal kinetic equation

$$\frac{dS_i}{dt} = k_i \frac{S_i}{S_{i0}}. \quad (6)$$

When equation (6) is integrated, we obtain:

$$\frac{S_e}{S_0} = \sum_{i=1}^N \alpha_i e^{k_i/L} \quad (7)$$

wherein:

$$\sum_{i=1}^N a_i = \sum_{i=1}^N \frac{S_{i0}}{S_0} = 1. \quad (8)$$

When $N = 1$, equation (7) coincides with Oleszkiewicz expression.

A similar approach was indicated independently by ECKENFELDER [7] in a work on kinetics of activated sludge process. The relationship (7), for $N = 2$, was compared with data obtained experimentally with pilot trickling filters filled with Cloisonyle tubes, fed with settled sewage and operated without recycle [4]. To evaluate gross removal coefficients K_1 , e , K_2 we used a suitable interpolation program. Figure 5 shows that the predictions

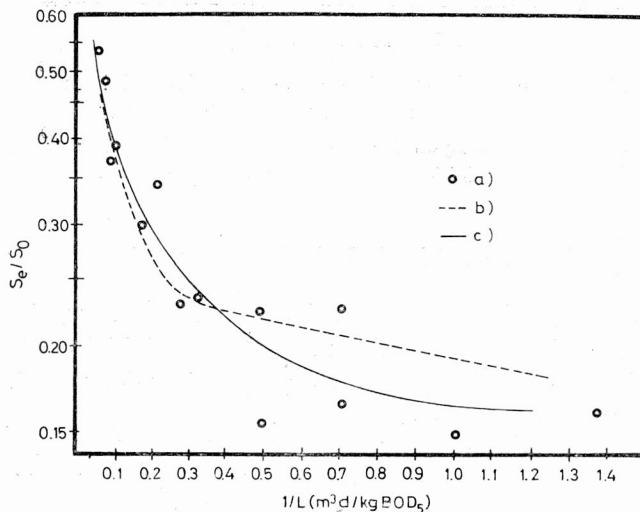


Fig. 5. Comparison between experimental data: a) from [4] and predictions from multisubstrate model; b) from (7) with $N = 2$; c) as b), but including also an apparent nondegradable substrate component
Rys. 5. Porównanie danych eksperymentalnych: a) z [4] z przewidywaniami z modelu wielosubstratowego; b) z (7) przy $N = 2$; c) jak b) ale uwzględniający również widoczny rozkładalny składnik substratu

of the model are in fair agreement (standard error: 13.27%) with the experimental data. It may be worth noting that the two components of substrate follow very different kinetics, i.e. $a_1 = 0.754$ of it is rapidly removed ($K_1 = 15.84$ kg BOD₅/m³ · d), the remaining $a_2 = 0.246$ is characterized by a much lower degradation rate ($K_2 = 0.2558$ kg BOD₅/m³ · d):

Figure 5 also shows that the better agreement with experimental data (standard error: 9.36%) is given by a relationship including also an apparent non-degradable substrate

$$(S_e S_0 = a_1 e^{-K_1/L} + a_2 e^{-K_2/L} + \beta, \text{ where } a_1 = 0.526, a_2 = 0.315, \beta = 0.159, \\ K_1 = 27.204, K_2 = 4.128).$$

4. CONCLUSIONS

Presently existing models are not suitable for the design of all trickling filters as they usually refer to a narrow range of operating conditions and to different packing media. Rigorous models which should take into account all the factors involved in mass transfer and biochemical reaction do not seem to be of much practical use. A promising approach suggested by the authors refers to the semi-empirical models and considers both the influence of the actual residence time distribution and the existence of different substrate removal mechanisms (physicochemical flocculation and adsorption; biochemical reaction); the latter factor can be described by a multicomponent substrate kinetics. Comparison with experimental data shows that a good agreement with such a model is achieved, especially if an apparent non-degradable substrate is also taken into account.

For more adequately verifying the proposed model experimental research should be carried out on pilot or full scale plants at different substrate concentrations in a narrow range of hydraulic loads; these plants should operate once through in order to eliminate the interfering and often counteracting effects of recycle.

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ANALIZA RACJONALNYCH METOD KONSTRUOWANIA FILTRU ZRASZAJĄCEGO

W pracy analizuje się główne półempiryczne modele dla konstrukcji filtrów zraszających stosowanych obecnie. Proponuje się modyfikację tych modeli, aby otrzymać lepszą zgodność z rzeczywistą dynamiką systemów przez nie reprezentowanych. Opracowano nowy model dla wieloskładnikowego podłoża, zwracając uwagę na jego zgodność z danymi ze szczególnie wiarygodnej literatury.

DIE ANALYSE RATIONELLER KONSTRUKTIONSMETHODEN VON BERIESELUNGSFILTERN

Analysiert werden vorwiegend semi-empirische Modelle die zur Konstruktion von zeitgenössischen Berieselungsfiltren dienen. Vorgeschlagen wird die Abänderung dieser Modelle im Sinne einer besseren Übereinstimmung mit der effektiven Dynamik der Systeme welche sie vertreten. Erarbeitet wurde ein neuer Modell für eine Mehrstoffbetung wobei ein besonderer Augenmerk dem Einklang mit den Angaben der glaubwürdigen Literatur geschenkt wurde.

АНАЛИЗ РАЦИОНАЛЬНЫХ МЕТОДОВ КОНСТРУИРОВАНИЯ ОРОШАЮЩЕГО ФИЛЬТРА

В работе анализируются главные полупырические модели для конструкции применяемых в настоящее время орошающих фильтров. Предложена модификация этих моделей для получения лучшего соответствия с реальной динамикой систем, представленных этими моделями. При учёте соответствия с данными, помещёнными в достоверной литературе, была разработана новая модель для многокомпонентного основания.