A SCALE-UP DESIGN PROCEDURE FOR ROTATING BIOLOGICAL CONTACTORS

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Abstract A scale-up design procedure, based on a new physical mass transfer (PMT) model, which describes the performance, for aerobic rotating biological contactors (RBC's) is developed. This scale-up procedure can be used to determine the disc surface area needed to prevent an oxygen limitation or to obtain a specific degree of treatment. In contrast to the empirical, and most previous RBC performance model, a major advantage of the PMT model in design is that it can predict the onset of oxygen limiting conditions since it accounts for the fact that low dissolved oxygen concentrations can limit the growth rate of the attached microorganisms. The PMT model can be used to predict the oxygen limiting loading rate so that this loading rate is not exceeded in practice. The proposed procedure has been successfully applied to design and install two relatively small full-scale domestic RBC units in parallel treating a cement plant wastewater efficiently.

Key Words Rotating Biological Contactors, Scale-Up, Design, Modelling, Wastewater Treatment

چکیده هدف این تحقیق ارائه روشی جدید برای بزرگنمایی صنعتی و طراحی بر مبنای یک مدل ریاضی کاربردی بر پایه درک کامل از اصول اساسی فرآیندها است. راکتور بیولوژیکی چرخان که برای نخستین بار در سال ۱۹۶۰ میلادی تولید تجارتی آن برای تصفیه هوازی فاضلاب در کشور آلمان غربی سابق شروع شد و از آن به بعد کاربرد گسترده ای در تصفیه فاضلابهای خانگی و صنعتی داشت، مد نظر است. در تمام فرآیندهای پیچیده مثل راکتورهای بیولوژیکی چرخان در تصفیه فاضلابهای خانگی و صنعتی، بزرگنمایی صنعتی نتایج آزمایشگاهی برای پیش بینی عملکرد سیستم در مقیاس بزرگ صنعتی امر بسیار مشکلی است. مدلسازی اختلاف در رفتارهای هیدرودینامیکی و انتقال جرم این راکتورها با اندازه های مختلف مشکل است. توجه به بزرگنمایی در طراحی راکتور بیولوژیکی چرخان بیشتر متمرکز بر سرعت محیطی دیسکها بعنوان متغیر اساسی طراحی است. اگر چه بزرگنمایی بر اساس سرعت محیطی ممکن است بدلیل ماکزیمم میزان حذف آلودگی بدست آمده مناسب بنظر آید، اما مشکل حذف آلودگی در مقیاس آزمایشگاهی آن این است که میزان حذف در مقیاس صنعتی را بیش از اندازه واقعی برآورد می کند. پیچیدگی فرآیند بیولوژیکی چرخان بیشتر از آن است که بشود آنرا با یک متغیر واحد مثل سرعت محیطی دیسکها بیان کرد. تشابه هندسی، سینماتیکی، دینامیکی و شیمیایی (انتقال جرم) با سیستم در مقیاس بزرگ مربوطه باید در نظر گرفته شود. این مهم با شناسایی گروهها و متغیرهای مهم بی بعد و ثابت نگه داشتن آنها در سیستم در مقیاس کوچک و بزرگ حاصل خواهد شد. شناسایی مهمترین متغیرهای بی بعد و بکار بردن مقادیر یکسان و ثابت این متغیرها از مقیاس کوچک به بزرگ در سیستمهایی نظیر راکتور بیولوژیکی چرخان که دارای رفتار پیچیده هستند غالباً غیر ممکن است. تا بحال هیچ روش و دستورالعمل اثبات شده ای در بزرگنمایی و طراحی از دیسکهای با قطر کوچک به دیسکهای با قطر بزرگتر پیدا نشده است. در این شرایط، یک مدل ریاضی جامع، حتی اگر دارای دقتی بسیار بالا نباشد، ابزار مفیدتری برای طرح و بیان مطالعات آزمایشگاهی است. بر اساس نتایج بدست آمده از این تحقیق، پیشنهاد شده است که یک مدل جدید انتقال جرم فیزیکی می‌تواند به خوبی بعنوان مبنا و دیدگاهی صحیح و منطقی در بزرگنمایی نتایج آزمایشگاهی تصفیه فاضلاب راکتور بیولوژیکی چرخان و در نتیجه روش و دستورالعملی نو بمنظور طراحی این راکتورها مورد استفاده قرار گیرد.

1. INTRODUCTION

A major demerit of an RBC compared to a dispersed growth reactor (activated sludge) is that the former is incompletely understood. The lack of fundamental understanding means that modelling and design procedures are not as rigorous and advanced as for dispersed growth systems and RBC systems are often under and sometimes overdesigned. The lack of understanding of the process fundamentals is further highlighted by the significant problems associated with the prediction of prototype performance based on the results of bench-scale experiments. Problems of this nature are further exacerbated when the nature of the wastewater to be treated is unknown [1].

In the absence of a good fundamental understanding of the RBC process, individual RBC manufacturers (typically see Envirex Inc.[2]) have developed their own empirical design procedures based on design curves, equations and guidelines arising from operational data obtained from their own equipment. The absence of standard design and operating procedures has been identified as one of the main reasons for the relatively slow acceptance for the use of RBC's [3,4].

It is clear that although robust semi-empirical procedures have been developed for specific RBC systems, they are inadequate for general application and predictive design. Only better understanding of the fundamentals of the RBC process incorporated in the advanced mechanistic models under development will enable successful initial design and increased process control in the future [3,5].

2. SCALE-UP IN RBC DESIGN

Early development work with RBC technology was performed with full-scale systems treating primarily municipal wastewater and little work was done on investigation of scale-up of data from bench- and pilot-scale reactors. Attempts at scale-up have focused mostly on peripheral or tip speed as the critical parameter, apparently because (1) early work with full-scale RBC's indicates that removal efficiency increases with increasing peripheral speed to a maximum of approximately 60 ft/min (0.3 m/s) [6,7], which corresponds to a rotational speed of 1.6 rpm for a 12-ft (3.7-m) diameter full-scale disc, and (2) it has been assumed that scale-up based on peripheral speed would enable simulation of full-scale shear force distributions (which control biofilm thickness) at a small scale and substrate removal rates naturally depend on the amount of active biomass present. Thus, most bench- and pilot-scale units have been operated at the same peripheral speed as full-scale units. If shear force control the amount of biomass present and the radius and peripheral speed of a disc affect shear forces, then scale-up based on peripheral speed may be valid.

To achieve the same peripheral speed as a large unit, a small disc must be rotated at higher rotational speed. Peripheral speed is related to disc diameter as follows:

$$V_p = \Omega r = 2\pi\omega r = \pi\omega d \tag{1}$$

Where V_p = peripheral speed, m/min
r = disc radius, m
d = disc diameter, m
ω = rotational speed, rpm
Ω = angular velocity, rad/min

This indicates that a 1-ft (0.3-m) diameter disc achieves the optimal peripheral speed at a rotational speed of 19 rpm. Operation of a small-scale RBC at this rotational speed, however, does not guarantee the same radial distribution of shear force between the attached biofilm and the wastewater. Schlichting [8] has developed an equation for the circumferential component of the shear stress near the surface of a completely submerged disc as a function of the disc radius:

$$\tau_s = 10^{-3}\, r\, \rho\, \nu^{0.5}\, \Omega^{1.5} \tag{2}$$

Where τ_s = shear stress, N/m^2
r = disc radius, m
ρ = liquid density, kg/m^3
ν = liquid kinematic viscosity, centistokes (10^{-6} m^2/s)
Ω = angular velocity, rad/min

This shows that the shear stress between the wastewater and the attached biofilm depends on the properties of the wastewater, the disc radius, and the angular velocity of the disc. Equation 2 indicates that the shear force exerted on the tip of a 1-ft (0.3-m) diameter disc rotating at 19 rpm is greater than the force exerted on the tip of a 12-ft (3.7-m) diameter disc rotating at 1.6 rpm. The rotational speed needed to provide a shear force on a 1-ft (0.3-m) diameter disc equal to that on a partially submerged, full-scale RBC disc would be lower than 19 rpm. An equation for the shear on a partially submerged disc is difficult to derive because of the mathematical complexity of describing the unsymmetrical geometry.

The complexity of the RBC process is greater than can be described with a single variable such as peripheral speed. Geometric, hydrodynamic, and chemical (mass transfer) scale-up factors are involved. In the classical similitude approach to scale-up, small-scale tests are designed such that geometric, kinematic, dynamic, and chemical similarity with a corresponding large-scale system is achieved. Identifying important dimensionless groups and variables for the process and keeping them the same in the small-scale system as in the large-scale system achieve this. As noted by Bisio [9], Himmelblau [10], and Lin *et al.* [11], identification of the most important dimensionless parameters and maintaining constant values for these parameters from small-scale to full-scale is often impossible for systems characterised by complex phenomena. The operation of an RBC typifies such complex behaviour. In such cases, a mechanistic model, even if not highly accurate, is a more useful tool for planning and interpreting experimental scale-up studies.

The oxygen transfer rate is a factor known to be important in full-scale RBC systems and one of that has posed problems for scale-up of results from small-scale RBC units. As noted earlier, most previous small-scale RBC studies have been performed using high rotational speeds to reproduce the disc peripheral speed of a full-scale RBC unit. However, by operating at high rotational speeds, the biomass in bench-scale units is exposed to both air and wastewater more often than in full-scale units. Increased oxygen transfer to the attached liquid film and greater wastewater mixing in bench-scale units operating at high rotational speeds have consistently caused higher substrate removal rates than are achievable at full-scale [7]. Although scale-up based on peripheral speed may have seemed suitable because of the maximum removal rates achieved, a problem with scale-up using this method is that bench-scale removal rates overestimate full-scale removal rates. To date, no proven method of scale-up from small diameter discs to larger diameter discs has been found. The scale-up relationship appears to be a complex function of disc diameter, wastewater organic loading rate, and disc rotational speed. Therefore, the latest USEPA review of RBC design [7] recommends not scale-up from disc diameters less than full-scale because it will likely yield a "non-conservative design".

Performance problems encountered by full-scale plants designed from smaller diameter RBC's operated at high rotational speeds usually occur in the first stages of multi-stage units [12,13]. The problem, referred to as substrate overloading of the first stages, occurs because first-stage substrate loadings are greater than oxygen transfer rates needed to maintain suitable first-stage dissolved oxygen levels. This problem is characterised by low first-stage dissolved oxygen concentrations (at or below 2 mg/l) and the appearance of nuisance organisms [13,14]. In domestic wastewater treatment plants, low first-stage dissolved oxygen concentrations lead to the growth of nuisance organisms which are tolerant of oxygen-deficient conditions, competitively colonise the RBC media surface and grow at lower metabolic rates than typical attached microorganisms. As the number of nuisance organisms increases, substrate removal rates decrease because of their lower metabolic rates.

A rational mechanistic model eventually may be useful for direct application to full-scale once more intermediate-scale testing (pilot-scale study) with RBC's is performed and after a better understanding of the difference in shear force distribution and biofilm thickness between bench- and full-scale units is achieved. In regard to the latter, while the effect of shear forces on the biofilm may be an important scale-up consideration, no studies have been performed to investigate how attached biofilms on bench-, pilot-, or full-scale RBC units are affected by the radial dependence of shear forces believed to be responsible for biomass sloughing. Biofilm thickness and mass have been shown to vary with shear stress in bench-scale experiments with annular biofilm reactors [15,16], but the radial distributions of shear stress and biofilm thickness have not been studied. In current models of RBC performance, it is assumed that the biofilm thickness is constant across the surface of the disc and that substrate utilisation rates are radially uniform. More realistic formulations await experimental investigation of the radial dependence of shear stress and biofilm thickness in RBC reactors. Such data would enable improvement of RBC

Figure 1. RBC Design curves developed by Envirex Inc.[2] for BOD removal from domestic wastewater using a mechanically - driven unit.

models and would shed considerable light on the RBC scale-up dilemma. At present, the information (embodied in fitted model constants) provided by a model developed from bench scale data may not be directly transferable to full-scale, but it does provide a basis for design of larger scale systems, for example, a pilot unit.

3. CURRENT RBC DESIGN PROCEDURES

As mentioned in the previous section, most full-scale RBC treatment plants have been designed using empirical design curves provided by RBC manufacturers. Most full-scale RBC's in operation treat domestic wastewater and ample data have been collected to develop the design curves. An example of an RBC design curve for treatment of domestic wastewater developed by Envirex Inc. [2] is shown in Figure 1. An alternative approach for RBC design is to use a graphical scale-up procedure [17], which is described in this section.

Empirical design curves for domestic wastewater treatment are not applicable to the treatment of industrial wastes because the compositions of industrial wastewaters vary from site to site and are not as uniform, or as well characterised, as domestic wastewater [18]. For wastewater other than domestic wastewater, the influent wastewater should be thoroughly characterised.

Clark et al. [17] presents a graphical design procedure derived from the work of Mcaliley [19], which is based on the use of hydraulic loading rates and the associated removal of substrate. The

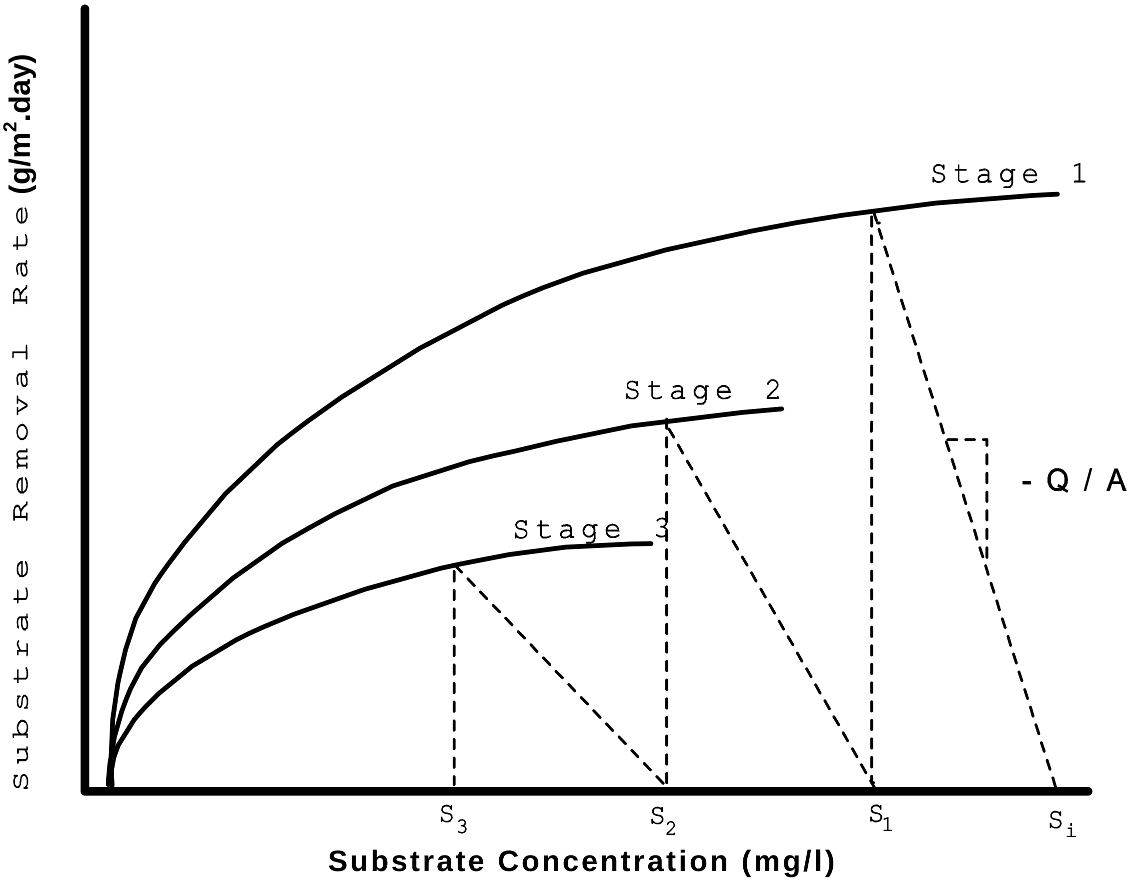

Figure 2. Hypothetical data to demonstrate a graphical RBC scale-up procedure [17].

design graph is shown in Figure 2, where it can be seen that the procedure is intended to enable calculation of the effluent substrate concentrations from each stage. This graphical design procedure for the removal of a single substrate can be accomplished by plotting substrate removal rates as functions of effluent substrate concentration for a three-stage RBC. Separate curves are drawn for each stage, as higher substrate removals are obtained for early stages. A full-scale RBC can be designed from this plot by knowing the influent flow rate, Q, and the influent and desired effluent wastewater concentrations and by assuming that the same substrate removal rates plotted in the figure will be attainable in the full-scale plant. The design area, A, can be obtained by guessing a Q/A ratio (hydraulic loading rate) and drawing a line with slope $-Q/A$ which starts at the influent substrate concentration and ends on the first-stage removal curve.

4. MODEL DEVELOPMENT

Initial Considerations The review of previous RBC models reveals a number of important factors to the development of a model to be used as a predictive design tool.

- Dissolved oxygen concentration in the trough appears to be an important factor for maintaining performance and should be included in such a model.
- The model should be applicable to different sites

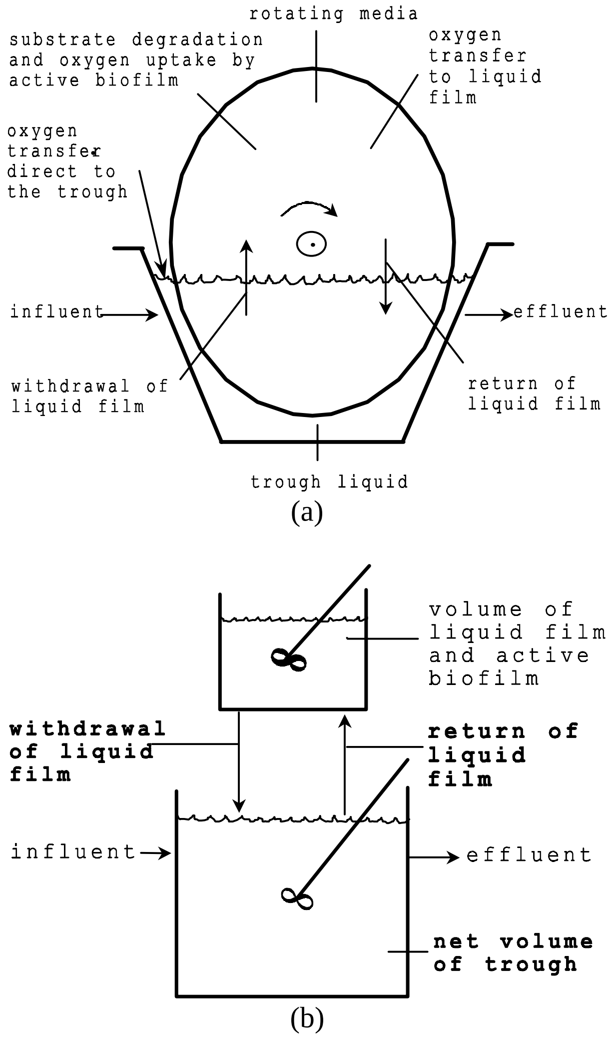

Figure 3. (a) The system and (b) model representation of an RBC with biofilm.

and designs and therefore can accommodate variations in such design features as media area, immersion depth, and rotational speed.
- In order to accommodate variations in design features, the model must include representations of the different physical conditions in RBC's, principally, the exposed biofilm and liquid film, the submerged biofilm, and the trough liquid.
- Substrate removal by suspended biomass in the trough liquid is assumed to be negligible compared to that of the attached biofilm.
- The assumption of Monod-type kinetics for substrate utilization is the most common although in most cases, either zero- or first-order approximations have been used.
- The most typical measurement of substrate concentration is filtered or soluble BOD or COD.

Model Features The principal features included in the model derive from the general observations made above and are as follows:
- Physical mass transfer of substrate and dissolved oxygen between the trough and the exposed film (exposed liquid film and biofilm) based on the diameter, depth of immersion, and rotational speed. This aforementioned model is henceforth called the physical mass transfer model (PMT model).
- Dynamic mass balance equations around the exposed film and the trough.
- Oxygen transfer to the exposed film and the trough surface.
- Double-limitation of the substrate utilisation rate with respect to substrate and oxygen concentrations (concentrations of both substrate and oxygen are used to determine the microbial substrate utilisation rate).

Model Assumptions A number of fundamental assumptions are required as follows:
- The substrate concentration can be represented by measurements of soluble BOD or COD.
- Each component of the model behaves as a completely-mixed reactor.
- Substrate utilisation is limited only by the availability (concentration) of substrate and oxygen.
- The mass of oxygen consumed per unit mass of substrate oxidised is constant.
- The yield coefficient is constant and incorporated into the overall substrate utilisation rate constant.
- Substrate removal by suspended biomass in the trough liquid is negligible. Other possible substrate removal mechanisms such as volatilisation of organic compounds are also neglected.
- The mass of active biofilm is constant.
- The biofilm is homogeneous and of uniform thickness.
- As the disc enters the trough, the liquid film exposed to the atmosphere is stripped off and mixed completely with the liquid in the trough.
- The exposed liquid film does not move relative to the media.

Conceptual Description of the PMT Model

The concept of the physical mass transfer (PMT) model is based on the representation of the system as two completely mixed reactors, the exposed film (exposed liquid film plus biofilm) and the submerged biofilm in the trough. As the media rotates, a film of liquid is drawn from the trough, the thickness of which depends on the velocity of extraction (disc speed). Flows into and out of each of these phases are related by mass balance and dependent on the proportion of media exposed and the rotational speed of disc. It is assumed that the phases remain stationary and behave as completely-mixed reactors (Figure 3).

It has been suggested that the molecular diffusion of substrate and dissolved oxygen within the biofilm is an important controlling factor in the operation of an RBC. However, the incorporation of such ideas in a performance model increases its complexity without necessarily increasing its accuracy. No reliable data exit for diffusivities of oxygen and substrate in biofilm. This lack of data is a good justification for considering an alternative method for mass transport of oxygen and substrate in an RBC. To this end, It is suggested that a suitable model for mass transport of oxygen and substrate is one in which there is advective transport to a lumped system comprising an exposed liquid film and active biofilm. This model enables a complete mass balance to be made and this notion incorporated in a performance model has been shown to produce valid results [20].

Model Equations Two types of mass balance equations are used in the PMT model: exposed film (exposed liquid film and biofilm) and trough. A mass balance of substrate around the exposed film gives:

Rate of mass accumulation = Rate of mass in - Rate of mass out - Microbial utilisation rate

$$\frac{dS_F}{dt} = \frac{Q_F}{V_{FE}} (S_T - S_F) - \frac{V_{FB}}{V_{FE}} r_s \qquad (3)$$

Where $S_F =$ substrate concentration in the film
$Q_F =$ "flow" through exposed film, $[L^3T^{-1}]$
$V_{FE} =$ volume of the exposed film
$S_T =$ substrate concentration in the trough
$V_{FB} =$ volume of the exposed active biofilm
$r_s =$ substrate utilisation rate, $[ML^{-3}T^{-1}]$

The substrate utilisation rate, r_s, is the most important term in the substrate mass balance equations because it accounts for all removal of substrate from the wastewater. This rate expression, the double Monod model, assumes both substrate and oxygen removal by microorganisms can be modelled using Monod kinetics and that the concentrations of both species influence the removal rate; therefore, no assumption needs to be made about which species, substrate or oxygen**,** controls the substrate removal:

$$r_s = k \frac{S_F}{K_s + S_F} \frac{C_F}{K_c + C_F} \qquad (4)$$

Where $k =$ maximum substrate utilisation rate, $[ML^{-3}T^{-1}]$
$K_s =$ substrate half-saturation constant
$C_F =$ dissolved oxygen concentration in the film
$K_c =$ oxygen half-saturation constant

A mass balance of oxygen around the exposed film gives:

$$\frac{dC_F}{dt} = \frac{Q_F}{V_{FE}}(C_T - C_F) + \frac{A_E}{V_{FE}} K_{LF} (\beta C_s - C_F) - \frac{V_{FB}}{V_{FE}} a\, k \frac{S_F}{K_s + S_F} \frac{C_F}{K_c + C_F} \qquad (5)$$

Where $C_T =$ dissolved oxygen concentration in the trough
$A_E =$ surface area of media exposed
$K_{LF} =$ oxygen transfer coefficient from air to the film, $[LT^{-1}]$
$C_s =$ saturation concentration of oxygen in water
$\beta =$ correction factor for saturation concentration of oxygen in wastewater
$a =$ oxygen utilisation coefficient, [-]

A mass balance of substrate around the trough gives:

$$\frac{dS_T}{dt} = \frac{Q}{V}(S_i - S_T) + \frac{Q_F}{V}(S_F - S_T) - \frac{V_{FS}}{V} k \frac{S_T}{K_s + S_T} \frac{C_T}{K_c + C_T} \qquad (6)$$

Where Q = volumetric influent/effluent flow rate, $[L^3T^{-1}]$

V = volume of the trough liquid

S_i = influent substrate concentration

V_{FS} = volume of the submerged biofilm

A mass balance of oxygen around the trough gives:

$$\frac{dC_T}{dt} = \frac{Q}{V}(C_i - C_T) + \frac{Q_F}{V}(C_F - C_T) + \frac{A_T}{V} K_{LT} (\beta C_s - C_T) - \frac{V_{FS}}{V} a\,k \frac{S_T}{K_s + S_T} \frac{C_T}{K_c + C_T} \quad (7)$$

where C_i = influent dissolved oxygen concentration

K_{LT} = oxygen transfer coefficient from air to the trough, $[LT^{-1}]$

A_T = surface area of trough liquid

Solution Method The system of nonlinear equations outlined above is solved simultaneously to predict concentrations of substrate and dissolved oxygen in each stage of a multi-stage RBC. The Newton-Raphson method for multi-dimensional systems (in this case, a 4×4 system) is used. The accuracy of convergence is set at 10^{-6} percent and the unknown substrate and dissolved oxygen concentrations are determined using a True BASIC program.

5. MODEL ASSESSMENT

It is important to test the predictions of the PMT model with operating data to ensure the validity of the model. The PMT model is calibrated and validated against high quality benchmark data obtained from plants treating different wastewaters. The approach taken for model evaluation is formulated in relation to the nature of the available data. The majority of data comprise averaged daily measurements covering a variety of plant designs, influent characteristics, and operating conditions. The first data set examined for model evaluation is that reported by Pike *et al.* [21] for the CJB-Stengelin single-stage unit treating primary-settled domestic wastewater at Kirk Hammerton Sewage Works, Yorkshire, U.K.. These data cover a range of operating conditions such as temperature and influent strength for a relatively constant influent flow rate. Parameter values are selected from literature and appropriate values of the substrate utilisation rate constant and the oxygen utilisation coefficient are found by trial and error. In order to examine the sensitivity of the model predictions to parameter variations, a simple sensitivity analysis has been undertaken by varying single parameters while keeping all others constant. Other data sets are those reported by Famularo *et al.* [22] for the Autotrol Bio-surf four-stage unit treating a papermill waste.

RESULTS AND DISCUSSION

a) CJB-Stengelin Single-Stage Unit Data

The data used for the initial evaluation has been abstracted from Pike *et al.* [21]. The performance data are described in Table 2 and comprise daily 24-hour composite samples over a year. As such they cover a temperature range from 6.6 to 15.3°C. The flow rate is kept largely constant while the influent BOD ranges from 65 to 305 mg/l. The PMT model predictions are made using parameter values obtained from the literature and manual model fitting.

The operating data are fitted to model by adjusting the model-fitting parameters. The model-fitting parameters adjusted to fit the model predictions to the data are the substrate utilisation rate constant at 20°C and the oxygen utilisation coefficient. The parameter search is by trial and error commencing from typical values reported in the literature. The PMT model is then fitted to a single day's data set (randomly selected) to determine effluent substrate concentration and dissolved oxygen concentration in the bulk liquid. The values chosen for each of the model parameters are summarised in Table 1.

The parameter values identified are then used in

TABLE 1. Values of Parameters Used to Model the Performance of the CJB-Stengelin Unit.

Parameter	Symbol	Value	Units
Air-to-Exposed-Film Oxygen Transfer Coefficient	K_{LF}	0.1	cm/min
Air-to-Trough Oxygen Transfer Coefficient	K_{LT}	0.61	cm/min
Substrate Half-Saturation Constant	K_s	100.0	mg/l
Oxygen Half-Saturation Constant	K_c	0.5	mg/l
Thickness of Active Biofilm	δ_B	150	μm
Thickness of Exposed Liquid Film	δ_L	52	μm
Substrate Utilisation Rate Constant at 20°C[a]	k_{20}	425	mg/l.min
Oxygen Utilisation Coefficient[a]	a	0.2	-
Correction Factor for Saturation Concentration of Oxygen in Water	β	0.9	-

[a] Model-fitting parameters.

the evaluation of remainder of the data sets and the steady-state solutions obtained are compared with the 24-hour composite sample measurements.

The variations in the input conditions and the model predictions for the CJB-Stengelin unit data are shown in Table 2. In general, there appears to be a reasonable correspondence between the model predictions and the observed data. Given the range of temperature and influent strength covered, the results give considerable confidence in the model structure and the suitability of the parameter values.

b) Autotrol Bio-Surf Four-Stage Unit Data

Famularo *et al.* [22] report a set of data for a four-stage Autotrol Bio-surf unit treating a relatively low-strength pulp waste (papermill A). The performance data are given in Table 4 and reported as average values taken after the pilot plant has operated at relatively steady-state conditions. In contrast to the CJB-Stengelin plant, as can be seen, the flow rate is not constant and the data are collected for a progressive increase in the flow rate.

Only the first-stage pilot plant data are simulated with the PMT model. There are two reasons for this. The first reason is that the greatest removal of substrate is achieved in the first stage of the Autotrol RBC unit at each hydraulic loading rate and very little organic carbon oxidation occurs in the final stages. The second reason for modelling only the first-stage data is that it is the only stage where dissolved oxygen concentrations may fall below the 2 mg/l level identified by other researchers as the concentration below which oxygen limiting conditions will exist.

The procedure used to find values for the model parameters and approach taken for model assessment are the same as those used for the CJB-Stengelin unit data so they are not discussed herein. The parameter values used in the model are given in Table 3 and as can be seen, the values are the same or in the same region as those found for the CJB-Stengelin unit. This consistency is a good indication of an appropriate model structure and the suitability of the parameter values. A comparison of model

TABLE 2. Comparison of Predicted and Observed S_T and C_T for the CJB-Stengelin Single-Stage Unit.

Date Data Set Obtained	Flow Rate Q (l/min)	Influent BOD S_i (mg/l)	Temperature T (°C)	Effluent BOD S_T (mg/l) Obs	Pre	DO Trough C_T (mg/l) Obs	Pre
9/02/77	4.52	150	6.6	20	17	-	6.8
16/03/77	4.21	158	7.6	14	14	-	6.7
27/04/77	4.20	179	8.9	18	16	3.0	5.0
25/05/77	4.21	305	12.6	30	27	2.2	3.2
13/07/77	4.39	188	14.2	16	15	4.0	4.5
24/08/77	4.49	189	15.3	10	15	2.3	4.2
3/10/77[a]	4.55	295	11.7	10	29	4.4	3.2
24/10/77	4.61	171	13.0	14	15	4.6	4.9
21/11/77	4.07	205	7.1	26	23	8.0	6.7
12/12/77	3.17	65	8.2	10	7	8.6	8.6

[a] This data set has an unusually low effluent BOD compared with similar days and appears to be suspect.

TABLE 3. Values of Parameters Used to Model the Performance of the Autotrol Bio-Surf Unit.

Parameter	Symbol	Value	Units
Air-to-Exposed-Film Oxygen Transfer Coefficient	K_{LF}	0.1	cm/min
Air-to-Trough Oxygen Transfer Coefficient	K_{LT}	0.98	cm/min
Substrate Half-Saturation Constant	K_s	100.0	mg/l
Oxygen Half-Saturation Constant	K_c	0.5	mg/l
Thickness of Active Biofilm	δ_B	150	μm
Thickness of Exposed Liquid Film	δ_L	67	μm
Substrate Utilisation Rate Constant at 20°C[a]	k_{20}	435	mg/l.min
Oxygen Utilisation Coefficient[a]	a	0.3	-
Correction Factor for Saturation Concentration of Oxygen in Water	β	0.9	-

[a] Model-fitting parameters.

predictions and measured performance is given in Table 4.

Table 4 shows that for most of the data points, there is a good agreement between the predicted and observed performance, particularly with respect to dissolved oxygen. The reasonable performance

TABLE 4. Comparison of Predicted and Observed Effluent BOD and DO Concentrations for the Autotrol Bio-Surf Unit[a].

Run Number	Flow Rate Q (l/min)	Temperature T (°C)	Influent S_i BOD	Influent C_i DO	Effluent BOD S_T (mg/l) Obs	Effluent BOD S_T (mg/l) Pre	DO Trough C_T (mg/l) Obs	DO Trough C_T (mg/l) Pre
2	44.47	21.7	77	7.2	29	32	2.8	2.8
4	88.94	18.9	74	8.1	45	45	4.8	4.3
6A	133.41	18.9	75	7.2	36[b]	53	3.5	4.2
6B	133.41	21.11	60	6.4	43	41	4.3	4.0
8	177.88	19.44	70	7.0	43	50	4.1	4.6
10	222.35	20.55	80	6.8	57	61	3.9	4.4

[a] Data for the first sage only.
[b] The effluent BOD of this data set is regarded as suspect.

of the PMT model under different operating conditions, compared to those of the CJB-Stengelin plant, provides confidence in its range of applicability.

The dissolved oxygen concentrations are more accurately predicted than those of the domestic waste data obtained from the CJB-Stengelin plant. The discrepancies for the domestic waste could be due to the onset of nitrification [23,24,25] which is not accounted for in the PMT model, whereas with papermill wastewater, the low nitrogen content would restrict any nitrification and hence any associated oxygen demand.

6. THE ROLE OF THE PMT MODEL IN DESIGN

The physical mass transfer (PMT) model attempts to predict the steady-state concentrations of soluble BOD and dissolved oxygen in each stage of a multi-stage RBC over a range of operating conditions and designs using a consistent set of parameter values. A major advantage of the PMT model for design is that it can predict the onset of oxygen limiting conditions as it accounts for the fact that low dissolved oxygen concentrations can limit the growth rate of the attached micro organisms, see Figure 4. The figure shows the oxygen limiting condition occurs, as predicted by the PMT model, at the point for loading rate of 7.74 g/m^2.day (oxygen-limiting loading rate). The data from Autotrol Bio-surf unit, run 2 [22] have been used as a typical example. It can be seen that when DO level falls below 2 mg/l, the rates of oxygen utilisation decrease due to the decline in metabolic rates. This is of great benefit from a design procedure since empirical and most previous RBC performance models all assume that oxygen does not limit substrate removal rates and thus cannot be used to predict the operating conditions which are oxygen limiting. The PMT model can be used to predict the oxygen-limiting loading rate so that this loading rate is not exceeded in practice.

The PMT model allows one to suggest an appropriate procedure to avoid the onset of oxygen limitations in RBC design. In order to avoid scale-up problems and simulate the full-scale oxygen transfer rates in small-scale units, the use of full-

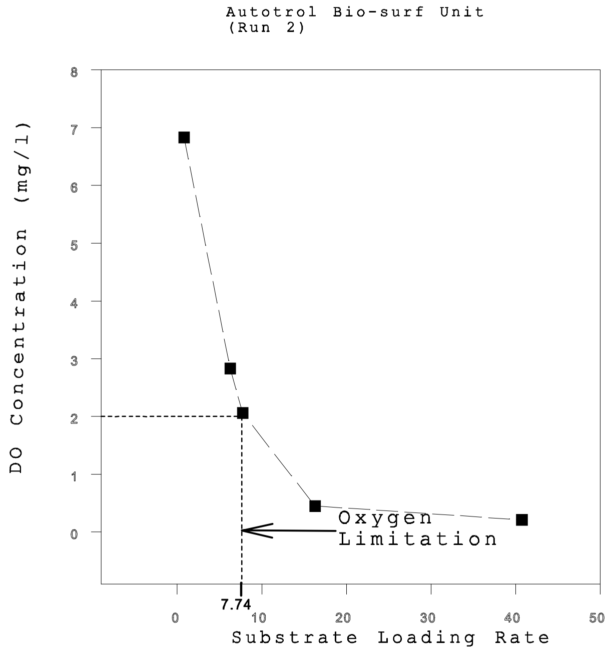

Figure 4. Sensitivity of predicted DO concentrations to change in the substrate loading rate (g/m^2 . day).

scale media diameter or rotational speed is recommended for prototype trials [3,7,26]. Figure 5 shows the model-predicted substrate removal rates at different rotational speeds (for the first stage of a two-stage RBC unit), in the manner used in Figure 2. The predicted removal curves level off like the idealised curves in Figure 2. As the design procedure presented by Clark et al. [17] incorporates hydraulic loading rate as the only design criterion and the PMT model accommodates the variation in rotational speed, it was decided to include rotational speed (which is an important scale-up factor and often found to vary from one manufacturer to another) in the graphical procedure. It seems that higher removal rates are obtained at higher trough substrate concentrations (higher substrate loadings) and higher substrate removal rates are obtained in the first stage. As can be seen, the rotational speed has profound effects on the predicted-substrate removal rates, higher rotational speeds result in higher removal rates. The effect of rotation on performance is strongly related to oxygen transfer and physical mass transfer to and from the biofilm. Operationally, the rotational speed and power consumption have to be balanced and the cost of operational control of rotational speed, for example, must be weighed against the advantages gained (higher rotational speeds are desirable to increase oxygen transport and to maintain thin biofilms). Note, however, that it is possible that, apart from mechanical reasons, there may be some hydrodynamic or mass transfer limitations on the maximum desirable rotational speed. Indeed as current operational speeds for RBC's are usually somewhat less than 10 rpm, this figure would seem to be a useful upper bound when using the PMT model.

An important effect not obvious in the removal curves of Figure 5 is the influence of oxygen limitation. If one of the design objectives is to prevent oxygen-limiting conditions, the graphical design procedure discussed above can be used as long as the oxygen limiting conditions are known. Fig. 5 shows where the oxygen limiting condition occurs in the pilot plant, as predicted by the PMT model, at the point for an effluent substrate concentration of 41 mg/l (associated with loading rate of 7.74 g/m^2.day and substrate removal rate of 17.49 g/m^2.day). An appropriate Q/A ratio should be selected so that first-stage substrate removal rates are constrained to the range where oxygen-limiting conditions will not occur. Again, the data from Autotrol Bio-surf unit, run 2 [22] operating at rotational speed of 2.92 rpm have been used as a typical example. For plant design using these curves, after selecting a suitable rotational speed, low dissolved oxygen concentrations can be avoided by using enough disc surface area (fixed by selecting an appropriate Q/A ratio) in the first stage so that the oxygen-limiting substrate loading is not exceeded. A low Q/A ratio results in a large amount of disc surface area which increase oxygen transfer via the attached liquid film on each disc and the desired dissolved oxygen concentration will be achieved. Maintaining the trough dissolved oxygen concentration near 2 mg/l has been successful in reducing the growth of nuisance organisms in the first stages of full-scale plants [12,13,14]. By selecting a higher rotational speed, the surface area required will decrease and might provide different ways of achieving the same degree of treatment by using fewer amounts of surface area. However, the cost-effective choice depends on several factors

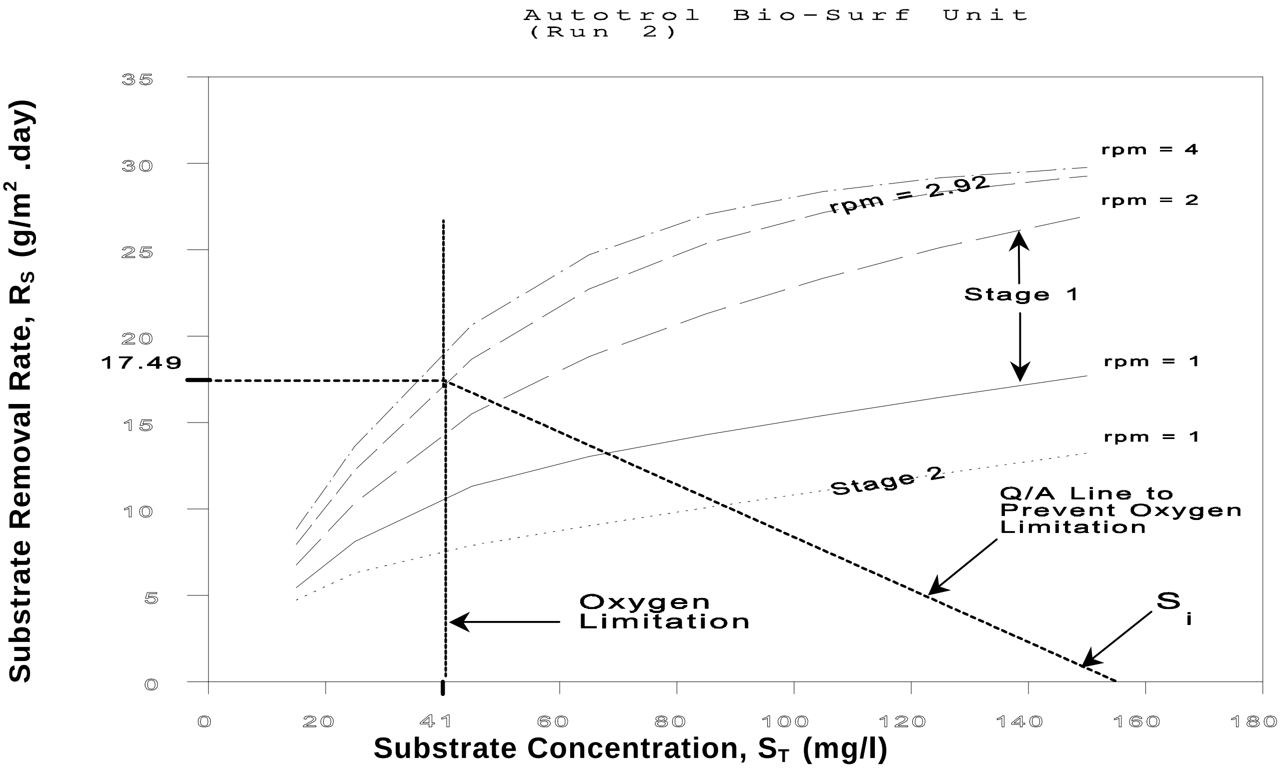

Figure 5. Predicted subtract removal rates as function of effluent subtract concentration demonstrating RBC scale-up to avoid oxygen-limiting condition.

including the cost and availability of media, power consumption, and the cost of operational control of higher rotational speed.

As an alternative to the graphical design procedure, the computer program used to implement the PMT model [20] can be modified to predict the surface area required to obtain a desired degree of treatment. There are two ways to modify the program. One way would be to take the disc surface area as an input variable and to run simulations to predict the effluent concentrations. This method would be useful because RBC manufacturers sell disc media in specific quantities. The other way that the program could be altered is to take the disc surface area as an unknown variable and to input the desired effluent substrate or dissolved oxygen concentrations. For example, to prevent oxygen-limiting conditions, the stage oxygen concentration could be fixed at 2 mg/l and the program could be used to calculate the disc surface area required and the effluent substrate concentration. It should be noted that when disc surface area is taken as an unknown variable, the governing equations have to be differential with respect to surface area in order to construct the new Jacobian matrix for solution using the Newton-Raphson method.

Finally, to show the applicability of the proposed procedure, it has been applied to design and install two small full-scale domestic RBC units in parallel treating 100 m^3/day of wastewater from a cement plant. The RBC's operate with relatively high removal efficiencies (maximum BOD effluent concentration of 25 mg/l) and produce no odour, nuisance organisms, and operational problems, which are prevalent in oxygen-deficient conditions.

7. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The main advantage of the PMT model for design is that it can predict the operating conditions where low dissolved oxygen concentrations limit substrate removal rates. Substrate removal data from RBC's operating at low rotational speeds can be modelled with the PMT model even if low dissolved oxygen levels are measured. The PMT model does not assume that adequate oxygen is available to support microbial growth like empirical and most existing RBC performance models. The most common operational problem in full-scale RBC's is substrate overloading of the first stages and the scale-up approach outlined above may be useful in preventing this problem in design. The PMT model may be useful as a design tool to predict the surface area needed to prevent an oxygen limitation or to obtain a specific degree of treatment given the influent substrate concentration, desired effluent concentration, wastewater flow rate, and a cost-effective rotational speed.

Neither the PMT model nor any of the other mechanistic models for RBC's can yet be used reliably to scale-up (extrapolate) data from bench-scale experiments to full-scale. This is primarily because of the lack of knowledge concerning the radial distribution of shear force and biofilm thickness on RBC discs. Investigation of the dependence of disc biomass thickness on the shear force distribution appears to be the appropriate next step for improving RBC mechanistic models and resolving the RBC scale-up dilemma.

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