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PHYSICAL MASS TRANSFER MODEL AND SCALE-UP DESIGN PROCEDURE FOR AEROBIC BIOREACTORS

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The scale-up design procedure based on new physical mass transfer model aerobic bioreactors 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 earliest rotating biological contactors performance model, a major advantage of the physical mass transfer model design is the prediction of 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.

Keywords: Physical mass transfer, Bioreactors, Scale-up design, Modeling.

1. Introduction

The major demerit of bioreactors compared to a dispersed growth reactor (activated sludge) is that the former is incompletely understood. The lack of fundamental understanding means that modeling and design procedure are not as rigorous and advanced as for dispersed growth systems. The bioreactors are often under and sometimes over designed, also lack of understanding of the process fundamentals. When nature of the wastewater is unknown then the prediction of prototype performance based on the results of bench-scale experiments are further exacerbated and effected scale-up design procedure [1].

In the absence of a good fundamental understanding of the rotating biological contactor's operations, individual rotating biological contactors manufacturers [2] have developed their own empirical design procedure based on design curves, equations and guidelines arising from operational data obtained from their own equipment. The development of a reliable unit of fixed size is readily achievable with the user feedback of an empirical design. It is clear that although robust semi-empirical procedures have been developed for specific bioreactor systems, they are inadequate for general applications and predicative design.

2. Scale-up Design for Bioreactors

Early development work 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 stage have focused mostly on peripheral or tip speed as the critical parameter, apparently because [3] early work with full-scale indicates that the removal efficiency increases with increasing peripheral speed to a maximum of approximately 0.3 m/s [4] which corresponds to a rotational speed of 1.6 rpm for a 3.7 m diameter full scale disc, and 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 [5]. 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:

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$$V_p = \Omega r = 2\pi\ \omega = \pi\ \omega\ d \qquad (1)$$

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 0.3 m diameter disc achieves the optional peripheral speed at a rotational speed of 19 rpm, under operation of a small-scale force between the attached biofilm and the wastewater. An equation for the circumferential component, the shear stress nears the surface of a completely submerged disc as a function of the disc radius [6].

$$\tau_s = 10^{-3}\ r\ \rho\ v^{0.5}\ \Omega^{1.5} \qquad (2)$$

where T_S = shear stress, N / m^2

r = disc radius, m
ρ = liquid density, kg / m^3
v = liquid kinematic viscosity, centistokes (10^{-6} m^2 / s)
Ω = angular velocity, rad / min.

Equation (2) indicates that the shear force exerted on the tip of a 0.3 m diameter disc rotating at 19 rpm is greater than the force exerted on the tip of a 3.7 m diameter disc rotating at 1.6 rpm. The rotational speed needed to provide a shear force on a 0.3 m diameter disc equal to that on a partially submerged, full-scale 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 design process increases when more process variables were involved than a single variable such as peripheral speed. Geometric (size, shape and volume etc.), hydrodynamic, and mass transfer factors are involved in scale-up designing of bioreactors. 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. As identification of the most important dimensionless parameters and maintaining constant values for these parameters from [2, 7, 8] small-scale to full-scale is often impossible for systems characterized by complex phenomena. 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 an important factor, has posed problems for scale-up designs at high rotational speeds, the biomass in bench-scale unit 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 [4]. Although scale-up based on peripheral speed may seem 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, on 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 United State Environmental Protection Agency (USEPA) review of design recommends not scale-up from disc diameter less than full-scale because it will likely to yield a non-conservative design [4].

Performance of rotating biological contactors decreases on scale-up design, with high rotational speed and small diameter [9, 10]. Usually in the first stage of multi-stage units 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 characterized by low first-stage dissolved oxygen concentrations (≤ 2 mg/l) and the appearance of nuisance organisms [11, 12]. Low dissolved oxygen concentrations in domestic wastewater treatment plants, the growth of nuisance organisms were tolerant by oxygen-deficient conditions, competitively colonies of organisms, the reactor media surface and grow at lower metabolic rates, etc. As the number of nuisance organisms increases, substrate removal rates decrease because of their lower metabolic rates. The most common nuisance organisms are in the *Beggiatoa* family. They are easy to identify because of their milky-white appearance and are sulphide-oxidising organisms that create an unpleasant odour compared to a healthy disc culture. In operating plants, the problem of substrate overloading can be corrected by additional oxygen to the first stage [10]. In the design of new facilities, more disc surface area can be used in the first stage to increase the oxygen transfer rate to the tank (via attached liquid film on the additional discs), compared with the substrate loading applied [11].

A rotational mechanistic model eventually may be useful for direct application to full-scale designs. Once more intermediate-scale testing (pilot-scale study) with rotatory biological contractors, the effect of shear forces on the biofilm may be important scale-up consideration. No studies have been performed to investigate how attached biofilms on bench-, pilot-, or full-scale units are affected by the radial dependence of shear force 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 [13]. But the radial distributions of shear stress and biofilm thickness have not been studied. Shear forces are responsible for maintaining a particular biofilm thickness. Such dependence might exist, but it is also conceivable that an attached liquid film helps to maintain a constant bio-film thickness across the disc by acting as a boundary layer between the biofilm and the through liquid. In current models of rotating biological contactors performance, it is assumed that the biofilm thickness is constant across the surface of the disc and that substrate utilization rates are radially uniform. More realistic formulations await experimental investigation of the radial dependence of shear stress and biofilm thickness in bioreactors. Such 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 Rotating Biological Contractors Design Procedure

As mentioned in the previous section, most full-scale bioreactors / biowaste treatment plants have been designed using empirical design curves provided by manufacturers. Most full-scale bioreactors operation treat domestic wastewater and ample data have been collected to develop the design curves. An example of a rotating biological contactors' design curve for treatment of domestic wastewater is shown in Fig.1. An alternative approach for the design is to use a graphical scale-up procedure, which is described, in this section [14, 15, 16].

Empirical design curves for domestic wastewater treatment are not applicable to the treatment of industrial wastes because the composition of industrial wastewaters varies from site to site and is not as uniform as domestic wastewater [17]. Industrial units operate at a different temperature than laboratory units, also may operate under a wider range of influent substrate loading conditions. Another important difference between the performance of laboratory-scale, or pilot-scale, and full-scale is an adequate

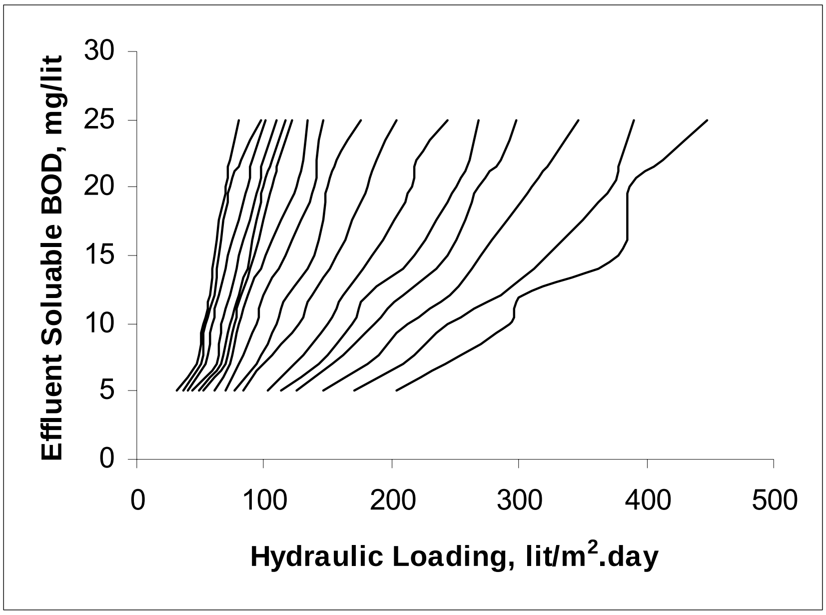

Figure 1. Rotating biological contactors design curve for biological oxygen demand removal from domestic wastewater by mechanical means.

supply of oxygen available to the attached microorganisms. Temperature elevation and salinity affect the solubility of oxygen in water [18].

The experimental data shown in figure 1 is based upon sixteen batches run on rotating biological contactor with different hydraulic rates. Each curve shows one experiment; drawn on the basis of hydraulic loading (one batch per day) and their effluent soluble biological oxygen demand. The curves show that with the increase in hydraulic loading in rotating biological contactor the effluent soluble oxygen demand will increases. These operating parameters of rotating biological contactors enhance the actual design with respect to oxygen demand on hydraulic loading.

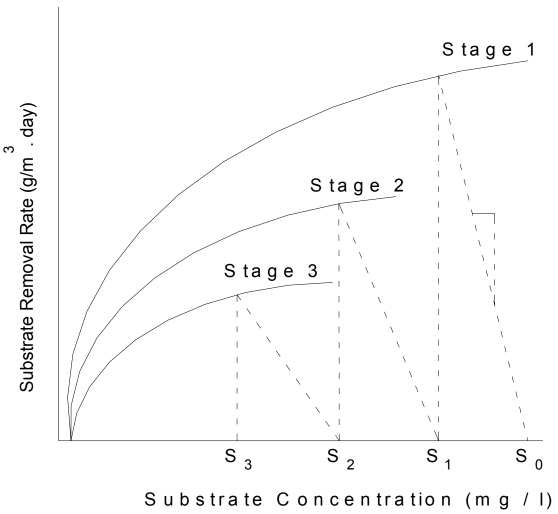

Figure 2. Hypothetical simulated data for rotating biological contactors scale-up procedure.

Some of these issues have been considered in the empirical procedures provided by manufacturers, but procedures for scale-up of bench- and pilot-scale treatment data are still being evaluated. The graphical design procedure [15, 19], which is based on the use of hydraulic loading rates and the associated removal of substrate. The substrate removal rate is show graphically in Fig. 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, R_s, defined as $Q((S_i-S_T)/A)$ in g/day.m^2 as a function of effluent substrate concentration, S_T, for a three-stage. Where Q is flow rate, Si is initial concentration, S_T is substrate concentration and A is area of reactor. Separate curves are drawn for each stage, as higher substrate removals are obtained for early stages. Full-scale rotating biological contactors can be designed from this plot by knowing the influent flow rate, Q, and the influent and desired effluent wastewater concentration and by assuming that the same substrate removal rates plotted in the Fig. 2 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 a slope - Q/A which starts at the influent substrate concentration and ends on the first-stage removal curve. Dropping a vertical line to the abscissa gives the predicted substrate concentration in the first stage. The Q/A ratio can be varied for each stage to allow each stage to contain different surface area and might provide different ways of achieving the same degree of treatment by using fewer stages. The most cost-effective disc media arrangement is usually the one that provides the necessary degree of treatment by using the least total amount of disc media.

4. Role of the PMT Model in Bioreactors Design

The physical mass transfer (PMT) model attempts to predict the steady-state concentration of soluble biological oxygen demand (BOD) and dissolved oxygen in each stage of a multi-stage bioreactor over a range of operating conditions. The physical mass transfer model is calibrated and validated against high quality benchmark data obtained from plants treating different wastewater. The data cover a variety of plant designs, influent characteristics and operating conditions [20].

A major advantage of the physical mass transfer 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 microorganisms (Fig. 3). The figure shows that the oxygen limiting condition occurs, as predicted by the physical mass transfer model, at the point for loading rate of 7.74g/m^2.day (oxygen-limiting loading rate). The data from Autotrol Bio-surf unit, run 2 have been used as a typical example [21].

It can be seen that when dissolved oxygen level falls below 2mg/l, the rates of oxygen utilization decrease due to the decline in metabolic rates. This is of great benefit from a design procedure since empirical and most previous rotating

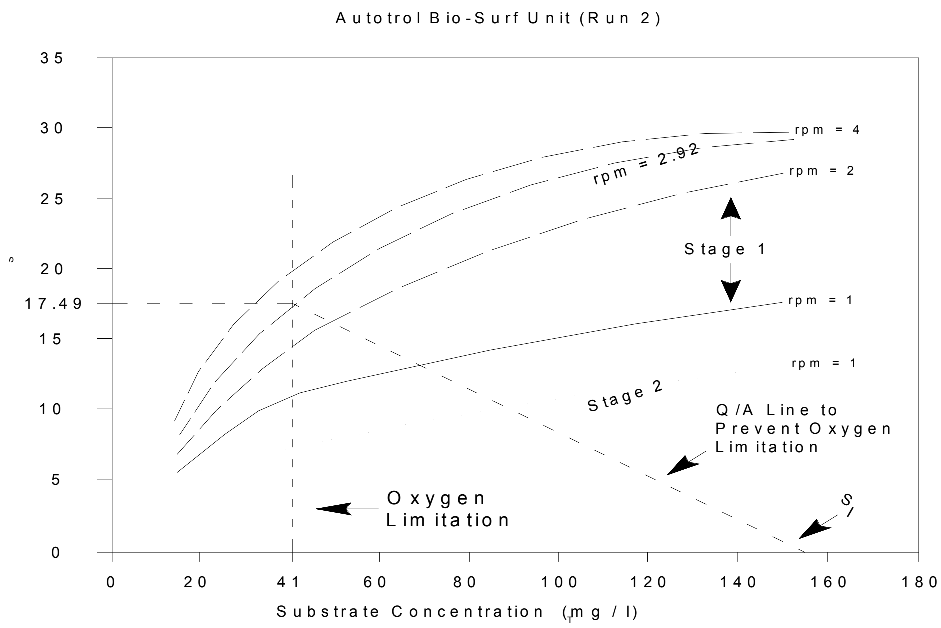

Figure 3. The influence of dissolved oxygen on substrate loading rate (g/m^2.day).

biological contactors performance models all assume that oxygen does not limit the substrate removal rates and thus cannot be used to predict the operating conditions which are oxygen limiting.

The physical mass transfer model can be used to predict the oxygen-limiting loading rate so that this loading rate is not exceeded in practice. In order to avoid scale-up problems and simulate the full-scale oxygen transfer rates in small-scale units, the use of full-scale media diameter or rotational speed is recommended for prototype trials [4, 9, 22]. Fig. 4 shows the model-predicted substrate removal rates at different rotational speeds (for the first stage of a two-stage unit), in the manner used in Fig. 2.

The predicted removal curves level off like the idealized curves in Fig. 2. As the design procedure presented [15, 23] incorporates hydraulic the physical mass transfer model accommodates loading rate as the only design criterion and 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 higher rotation speeds are desirable to increase oxygen transport and to maintain thin biofilms; however, it is possible that, apart from mechanical reasons, there may be some hydrodynamic or mass transfer limitations on the maximum desirable rotational speed [24].

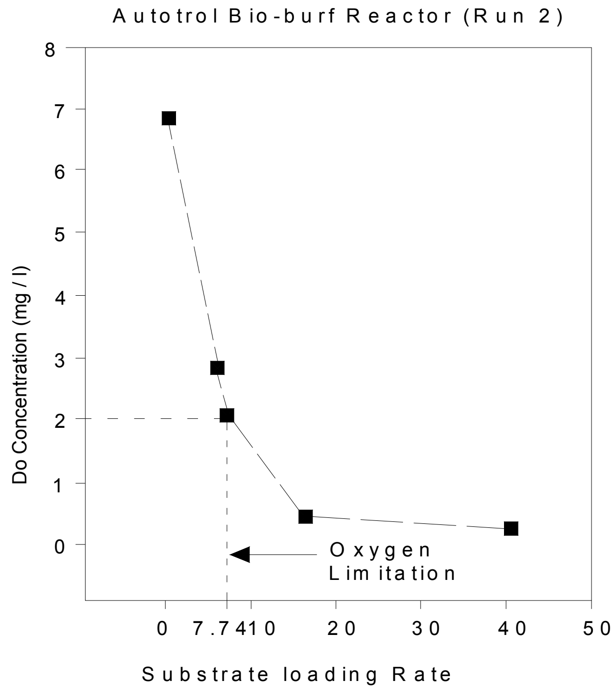

Figure 4. Substrate removal rate as function of effluent substrate concentration in RBC scale-up to avoid oxygen-limiting conditions

The important effect, not obvious in the removal curves of Fig. 4, 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. 4 shows, effluent substrate concentration of 41 mg/l occurs in the pilot plant, which was the same oxygen limiting condition as predicted by the physical mass transfer model. At the point (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.

The data from Autotrol Bio-Surf unit run 2, operating at rotational speed of 2.92 rpm have been used as a typical example [21]. Plant design using these curves, after selecting a suitable rotational speed, low dissolved oxygen concentrations, enough disc surface area (fixed by selecting as 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 increases oxygen transfer via the attached liquid film on each disc and the desired dissolved oxygen concentration will be achieved. Therefore, dissolved oxygen concentrations in the first stage of full-scale plant was maintained [10, 11, 13]. 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 amount of surface area.

As an alternative to the graphical design procedure, the computer program used to implement the [20] physical mass transfer model 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 [22]. The second way is that the program could be altered 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 dissolved 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.

5. Conclusions

So many important assumptions incorporated in the physical mass transfer model need to be verified before the model can be recommended as a valid design tool. First, the physical mass transfer model assumes that the attached biofilm thickness is constant across the surface of the disc. Measurements of biofilm thickness would also be helpful to determine if there is a radial dependence on the growth of attached biofilms and how this affects rotating biological contactors scale-up. The air-to-trough oxygen transfer rate may be lower in a large unit where the wastewater trough will be deeper and the water will not be as uniformly mixed as in bench, or pilot-scale units. Therefore, without additional data to compare the performance of bench-, pilot-, and full-scale, some modeling assumptions, currently, limit the applicability of this model for scale-up.

The physical mass transfer model for design predicts the operating conditions where low dissolved oxygen concentrations limit the substrate removal rates and substrate removal data. The physical mass transfer model does not assume that adequate oxygen is available to support microbial growth like empirical and most existing bioreactors performance models. The most common operational problem in full-scale design is substrate overloading of the first stage and the scale-up approach outlined above may be useful in preventing this problem in design. With some additional data comparing the biofilms bench-, pilot-, and full-scale design, the physical mass transfer model may be useful tool to predict the surface area necessary for a desired of treatment given the influent substrate concentration, desired effluent concentration, and wastewater flow rate.

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