

USE OF A ROTATING BIOLOGICAL CONTACTOR FOR APPROPRIATE TECHNOLOGY WASTEWATER TREATMENT

ABSTRACT

Organic loading (weight per unit time per volume) is useful for the design of rotating biological contactors (RBC). The present study emphasizes the significance of this control or design parameter, because it allows for the direct comparison of the RBC system's performance when operated under various circumstances and with different kinds of wastewater. The results of the paper prove that the COD removal in rotating biological contactor systems is a function of the organic loading rate. However, both the wastewater concentration and flow rate also influence the system's efficiency, but their impact can be combined by the effects of organic loading. Most of the removal of the COD (40-85% of the total removal, depending on the organic loading applied) occurs in the first stages of the system. There is a strong correlation between the organic loading and the concentration of suspended solids in the rotating biological contactor basin. At higher loadings higher concentrations are noted. At a loading of about (24g/m².d), the suspended solids were 225, 125, 35, and 25mg/L in the first, second, third and fourth stages respectively. To achieve an effluent quality of (BOD < 25mg/L, COD < 60mg/L), the system must be operated at organic loadings of about (22 gBOD/m².d and 65 gCOD/m².d) respectively. For the nitrification process, the system must be designed to operate at an organic loading of about (10g/m².d) or less, and the reactor or basin volume should be designed to achieve a hydraulic loading of about (40L/m².d) or less.

KEY WORDS

- BOD
- COD
- organic material
- wastewater
- biofilm

1. INTRODUCTION

A rotating biological contactor (RBC) is a successful wastewater microbial treatment system that has been developed. It has been widely used for the secondary treatment of domestic and industrial wastewater. An RBC contains a number of discs which are arranged along the shaft axis of the contractor. The wastewater is fed in the contactor at a certain flow rate. All the discs are partially submerged into the wastewater. When the discs are continuously rotated by a shaft, the lower portion of the discs submerged in the wastewater would then be turned to the upper atmosphere phase. Thus, the

microbial film on the disc that is initially in contact with the nutrients of the wastewater phase and the oxygen in the atmosphere would then perform its metabolism. Hence, the organic compounds in the wastewater would serve as the nutrients for the microbes to digest and grow. By such periodical operation, the microbes would grow, and a certain thickness of the sludge film would be obtained. The RBC is used because of its advantages such as high specific surface area, high activated sludge concentration, better sludge settling, process stability, and low maintenance and power consumption. Benefield and Randall (1980) described the design of biological treatment processes for wastewater in their book. Two



pilot-scale RBCs with PE discs arranged in four stages were used (Tokuz, 1989) for the treatment of synthetic wastewater containing 2-nitrophenol or 2-chlorophenol. Opatken and Bond (1991) treated a leachate with a high concentration of ammonia-nitrogen (20-1000 mg/L) by the nitrification process with a pilot-scale RBC. The surrogate leachate was adjusted to achieve various dissolved organic carbon concentrations. Different experiments were conducted to determine the operating parameters of the RBC treatment system. Buisman, *et al.* (1990) compared three different bioreactor systems for the removal of sulphides containing wastewater. A stirred reactor, biorotor reactor and upflow reactor were used for the comparison. The biomass support materials of Rassching rings and polyurethane were also compared. It is obvious that the biofilm disc is very important for observation of the RBC's performance. Brower and Barford introduced different biological fixed film systems in their report (Brower and Barford, 1997). In 1978, a theoretical model for RBC systems was provided so that the process design criteria for a pilot-plant RBC process could be established and compared with the activated sludge process (Clark, *et al.*, 1978). Since an RBC is composed of a series of discs with microbial growth in a film, the film model is certainly important to study. Mass transfer problems across the film should also be taken into consideration. Steady-state biofilm kinetic models were proposed for conditions of both deep and shallow biofilms (Rittmann and McCarty, 1980). In the model, a Monod growth model with a substrate diffusion along a single dimension was mainly assumed.

The film was assumed to be a planar form. The substrate flux was also discussed. Suidan and Wang (1985) followed the single-substrate biofilm model proposed by Williamson and McCarty in 1976. They further described a simple algebraic relationship between the substrate flux, substrate concentration in the bulk phase (or on the film's surface), and the biofilm's thickness. A deep biofilm model with a Monod assumption for completely mixed and plug flow biofilm reactors was analyzed (Suidan, 1986). Such biofilm reactors were found to be extremely sensitive to the surface parameters.

Until now, all the biofilm models have been based on Monod growth kinetics. In this article, in addition to the Monod assumption, substrate inhibition kinetics (or Haldane kinetics) were also assumed as the basis for developing a steady state biofilm kinetic model. This substrate-inhibition biofilm kinetic model was also compared with the Monod biofilm model. Arquiaga, *et al.* (1995) reported and compared the characteristic behaviors of the members of the genera *Pseudomonas* and *Bacillus* as well as others on the biological treatment of aircraft paint-stripping wastewater. The wastewater contained methylene chloride and phenol in concentrations of about 5,000 and 1,800 mg/L, respectively.

Activated sludge reactors and rotating biological contactors have demonstrated that both suspended and attached growths can be

effective methods for treating wastewater as described above. Sagy and Kott (1990) examined fecal coliform bacteria and *Salmonella typhimurium* die-off in an experimental RBC which received settled domestic sewage from a city's main sewer. The behavior of the microbes on the biofilm is fairly important. Most biofilms are formed by mixed species. Gupta and Gupta used a mixed culture aerobic biofilm to remove carbon and nitrogen from synthetic domestic sewage (Gupta and Gupta, 1999).

RBC is an essential treatment process for treating industrial wastewater. Moreover, it is also a very interesting system for theoretical analysis. Hence, in this work, we established a model for a biofilm system based on both Monod and substrate inhibition mechanisms. The operating conditions as well as the number of biofilm discs can be analyzed with these models.

2. DEVELOPMENT OF MATHEMATICAL MODEL

The biofilm reactor under consideration has a length of L_t and a flow direction parallel to the horizontal axis as shown in Fig. 1. The schematic biofilm is shown in Fig. 2. It was assumed that the fluid was well-mixed in the radial direction, and the substrate consumption from the suspended microbial can be negligible when compared to that of the attached biofilm.

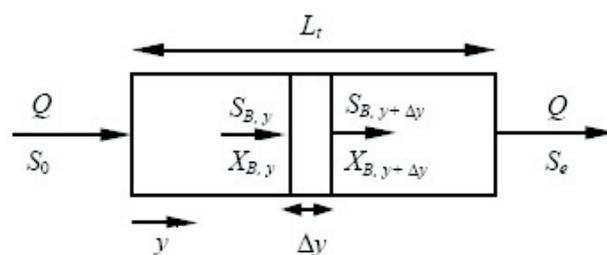


Fig. 1 Schematic plots of the biofilm reactors.

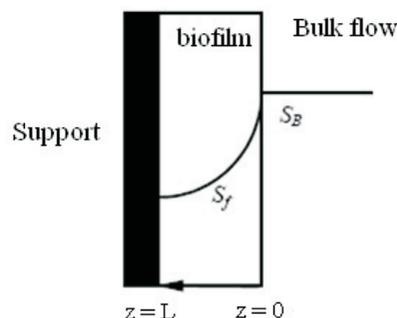


Fig. 2 Schematic plot of a biofilm.

Consider an infinitesimal volume in a biofilm reactor, by the mass balance for a shell,

$$\frac{\partial}{\partial t} \left(\frac{V_t}{L_t} \cdot \Delta y \cdot S_B \right) = (QS_B)_y - (QS_B)_{y+\Delta y} - R_a \cdot \frac{A_w}{L_t} \cdot \Delta y \quad (1)$$

where V_t is the volume of wastewater in the biofilm reactor, L_t is the length of the reactor, R_a is the substrate consumption rate by the microbial attached on the disc, S_B is the liquid phase substrate concentration, and Q is the flow rate. Dividing by Δy and letting $\Delta y \rightarrow 0$, we obtain

$$\frac{V_t}{A_w} \frac{\partial S_B}{\partial t} = -\frac{Q \cdot L_t}{A_w} \frac{\partial S_B}{\partial y} - R_a \quad (2)$$

If it is further assumed that the substrate consumption rate by the attached microbial on the disc is equal to the substrate diffusion rate on the surface of the film, then

$$\frac{V_t}{A_w} \frac{\partial S_B}{\partial t} = -\frac{Q \cdot L_t}{A_w} \frac{\partial S_B}{\partial y} + D_f \frac{dS_f}{dz} \Big|_{z=0} \quad (3)$$

where D_f is the diffusion coefficient of the substrate within the biofilm, S_f is the substrate concentration in the biofilm, and z is the axis along the biofilm's thickness. Under a steady state assumption

$$\frac{\partial S_B}{\partial y} = \frac{D_f \cdot A_w}{Q \cdot L_t} \frac{dS_f}{dz} \Big|_{z=0} \quad (4)$$

With the above basic equation having been established, different analyses for different conditions of the film's thickness will be described in the following section.

2.1 Thick biofilm

The boundary conditions for the thick film are

$$\begin{array}{lll} \text{B.C. 1} & S_B = S_0 & \text{at } y = 0 \\ \text{B.C. 2} & S_B = S_c & \text{at } y = L_t \end{array}$$

For the case of a thick biofilm with Monod kinetics, $\mu = \mu_m S / K_s + S$.

$$R_a = -D_f \frac{dS_f}{dz} \Big|_{z=0} = D_f \sqrt{2A \left[S_B + K_s \ln \left(\frac{K_s}{K_s + S_B} \right) \right]} \quad (5)$$

$$\text{Where } A = \frac{kX_f}{D_f}$$

and k is the maximum specific substrate consumption rate [t^{-1}].

For the case of a thick film with a substrate inhibition kinetic

$$\mu = \frac{\mu_m S}{K_s + S + S^2 / K_i}$$

(1) If $K_i/K_s < 4$, then

$$R_a = D_f \sqrt{A \left\{ K_i \ln \left(1 + \frac{S_B}{K_s} + \frac{S_B^2}{K_i K_s} \right) - \frac{2K_i^{1.5}}{\sqrt{4K_i - K_s}} \left[\tan^{-1} \left[\frac{2S_B + K_i}{\sqrt{K_i(4K_i - K_s)}} \right] - \tan^{-1} \left[\frac{K_i}{\sqrt{K_i(4K_i - K_s)}} \right] \right\} \right\}} \quad (6)$$

(2) If $K_i/K_s > 4$, then

$$R_a = D_f \sqrt{A \left\{ K_i \ln \left(1 + \frac{S_B}{K_s} + \frac{S_B^2}{K_i K_s} \right) - \frac{K_i^{1.5}}{\sqrt{K_i - 4K_s}} \ln \frac{[2S_B + K_i - \sqrt{K_i(K_i - 4K_s)}][K_i + \sqrt{K_i(K_i - 4K_s)}]}{[2S_B + K_i + \sqrt{K_i(K_i - 4K_s)}][K_i - \sqrt{K_i(K_i - 4K_s)}]} \right\} \right\}} \quad (7)$$

(3) If $K_i/K_s = 4$, then

$$R_a = -D_f \cdot \frac{dS_f}{dz} \Big|_{z=0} = 2D_f \sqrt{2AK_s \left[\ln \left(\frac{S_B}{2K_s} + 1 \right) - \frac{S_B}{S_B + 2K_s} \right]} \quad (8)$$

By substituting the above equations (Eqs. (5)-(8)) into Eq. (4), we obtain the following results for Monod kinetics (without substrate inhibition),

$$\frac{dS_B}{dy} = -\frac{D_f \cdot A_w}{Q \cdot L_t} \cdot \sqrt{2A \left[S_B + K_s \cdot \ln \left(\frac{K_s}{K_s + S_B} \right) \right]} \quad (9)$$

For Haldane kinetics (with substrate inhibition),

(1) If $K_i/K_s < 4$,

$$\frac{dS_B}{dy} = -\frac{D_f A_w}{Q L_t} \sqrt{A \left\{ K_i \ln \left(1 + \frac{S_B}{K_s} + \frac{S_B^2}{K_i K_s} \right) - \frac{2K_i^{1.5}}{\sqrt{4K_i - K_s}} \left[\tan^{-1} \left[\frac{2S_B + K_i}{\sqrt{K_i(4K_i - K_s)}} \right] - \tan^{-1} \left[\frac{K_i}{\sqrt{K_i(4K_i - K_s)}} \right] \right\} \right\}} \quad (10)$$

(2) If $K_i/K_s > 4$,

$$\frac{dS_B}{dy} = -\frac{D_f A_w}{Q L_t} \sqrt{A \left\{ K_i \ln \left(1 + \frac{S_B}{K_s} + \frac{S_B^2}{K_i K_s} \right) - \frac{K_i^{1.5}}{\sqrt{K_i - 4K_s}} \ln \frac{[2S_B + K_i - \sqrt{K_i(K_i - 4K_s)}][K_i + \sqrt{K_i(K_i - 4K_s)}]}{[2S_B + K_i + \sqrt{K_i(K_i - 4K_s)}][K_i - \sqrt{K_i(K_i - 4K_s)}]} \right\} \right\}} \quad (11)$$

(3) If $K_i/K_s = 4$,

$$\frac{dS_B}{dy} = -\frac{2D_f \cdot A_w}{Q \cdot L_t} \cdot \sqrt{2AK_s \left[\ln \left(\frac{S_B}{2K_s} + 1 \right) - \frac{S_B}{S_B + 2K_s} \right]} \quad (12)$$

The above equations are all first-order ordinary differential equations. They can be solved for the numerical solution of $S_B|_{z=L}$, which is the exit substrate concentration, S_e , by the fourth-order Runge- Kutta method.

2.2 Thin biofilm

In Eq. (4), $\left. \frac{dS_f}{dz} \right|_{z=0}$ is a function of S_B . In addition, for Monod kinetics,

$$D_f \frac{d^2 S_f}{dz^2} = k \cdot X_f \cdot \frac{S_f}{K_s + S_f} \quad (13)$$

For substrate inhibition kinetics,

$$D_f \frac{d^2 S_f}{dz^2} = k \cdot X_f \cdot \frac{S_f}{K_s + S_f + S_f^2 / K_i} \quad (14)$$

The boundary conditions for the case of a thin film are listed as follows:

$$\text{B.C. 1} \quad S_f = S_B \quad \text{at } z = 0$$

$$\text{B.C. 2} \quad \left. \frac{dS_f}{dz} \right|_{z=L_t} = 0 \quad \text{at } z = L_t$$

S_f and $\left. \frac{dS_f}{dz} \right|_{z=0}$ can be solved by a finite difference, and the exit substrate concentration $S_B|_{z=L}$ can be further obtained. Based on the above theorem and assumptions, the effluent substrate

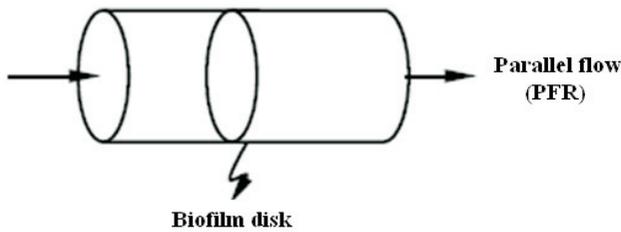


Fig. 3 Plots of the biofilm reactors for mathematical analysis.

concentration can be computed. During the computation process, several operating conditions, which exert an influence on the performance of the biofilm reactor, such as the influent substrate concentration, length of the reactor, total surface area of the biofilm, flow rate, amount of reactors in the series, and the film's thickness should be provided. The growth and diffusion parameters related to the biofilm such as K_s , K_i , k , X_f , and D_f should be given as well.

For the thin biofilm, under a Monod kinetics assumption, when the substrate concentration in the liquid phase is higher, the substrate consumption rate R_a would be higher as well. For a substrate inhibition kinetics assumption, the result is similar, which is a higher substrate consumption rate for a higher liquid phase substrate concentration. However, when the substrate concentration is too high, the substrate inhibition would cause a decrease in the substrate consumption rate. It can be seen from Fig. 3 that under a certain range of S_B , $\left. \frac{dS_f}{dz} \right|_{z=0}$ (R_a) is a linear function of S_B in the case of thin film. Therefore, $\left. \frac{dS_f}{dz} \right|_{z=0}$ can be expressed as

$$\left. \frac{dS_f}{dz} \right|_{z=0} = a \cdot S_B + b \quad (15)$$

where a is the slope and b is the intercept, a and b are dependent on the range of S_B . Provided that the liquid phase substrate concentrations were $S_{B,1}$ and $S_{B,2}$, then

$$\left(\left. \frac{dS_f}{dz} \right|_{z=0} \right)_{S_B=S_{B,1}} = a \cdot S_{B,1} + b \quad (16)$$

$$\left(\left. \frac{dS_f}{dz} \right|_{z=0} \right)_{S_B=S_{B,2}} = a \cdot S_{B,2} + b \quad (17)$$

Combining Eqs. (16) and (17), a and b can then be obtained. By substituting Eq. (15) into Eq. (4), then

$$\int_{S_{B,1}}^{S_{B,2}} \frac{dS_B}{a \cdot S_B + b} = \int_{y_1}^{y_2} \frac{D_f \cdot A_w}{Q \cdot L_t} dy \quad (18)$$

$$S_{B,2} = -\frac{b}{a} + \left(S_{B,1} + \frac{b}{a} \right) \exp \left(\frac{a \cdot D_f \cdot A_w \cdot \Delta y}{Q \cdot L_t} \right) \quad (19)$$

The 1st-order ordinary differential equation can thus be transferred into an algebraic equation so that the analysis of such a system is more efficient.

3. RESULTS AND DISCUSSION

Six stages of biofilm reactors for wastewater treatment were considered in the following analysis. Both a Monod kinetic and substrate inhibition kinetic were applied in this study. The length of the biofilm reactor was set to be 5.0 m. The total surface area for treatment was 5,000 m². The kinetic parameters for the cell growth were $K_s = 100$ mg/L and $X_f = 20,000$ mg/L. The diffusivity of the biofilm was $D_f = 0.02$ cm²/h. The flow directions of the influent feed were set to be parallel to the horizontal axis of the reactor. For a flow direction parallel to the axis, the biofilm reactor may be regarded as a plug flow reactor (PFR).

3.1 Effect of Hydraulic Loading

When rotating biological contactor systems were originally introduced, the design process was based on hydraulic loading expressed in (L/m².d) to achieve the required removals. In figure (4), the percent removals of the Chemical Oxygen Demand (COD) were represented versus the hydraulic loadings as a direct relationship. As noted, there is a strong correlation between these two parameters. Increasing hydraulic loadings scientifically decrease the performance efficiency of rotating biological contactor systems. In figure (5), the effect of hydraulic loading was represented versus the remaining organic loading in terms of (gBOD/m².d). As shown in the figure, increasing hydraulic loading increases the amount of organic loading remaining, which consequently decreases the efficiency of the system.

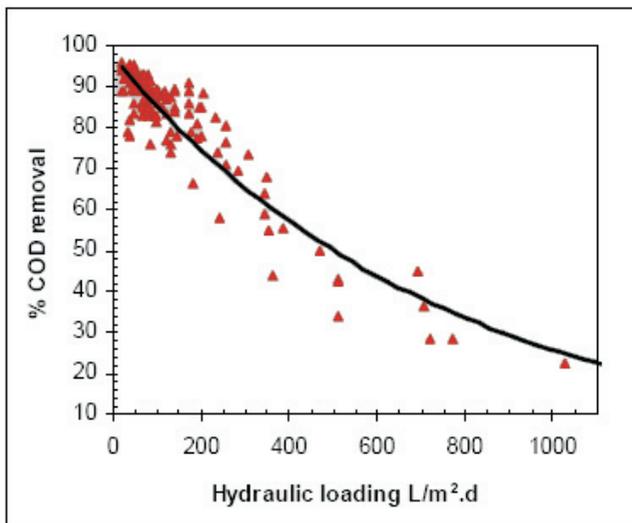


Fig. 4 Effect of hydraulic loading on % COD removal.

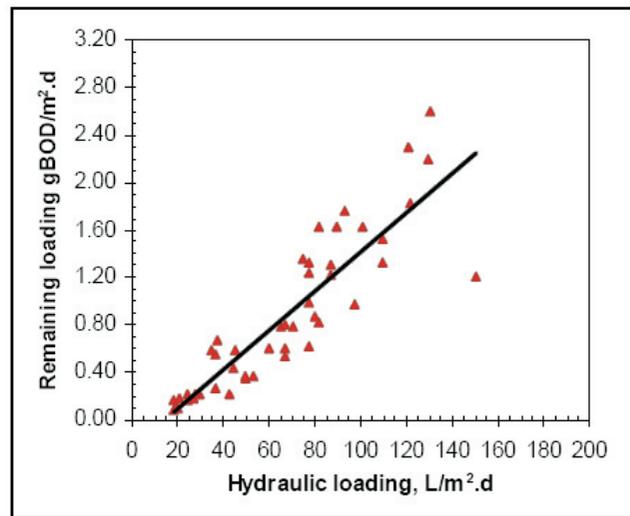


Fig. 5 Effect of hydraulic loading on remaining BOD in terms of gBOD/m².d.

In fact, the parameter (hydraulic loading) is directly joined with the concept of contact or detention time. A high hydraulic load combined with low organic concentrations in the wastewater can be treated satisfactorily as long as sufficient hydraulic detention time is available.

Conversely, a highly concentrated wastewater at a very low hydraulic load still requires adequate time for satisfactory treatment. At a constant flow rate, increasing organic concentrations causes an increase in the total amount of organic loading applied to the rotating contactor system. Likewise, at a constant organic concentration, increasing flow rates can cause an increase in the total amount of organics applied to the system.

Since both the flow rate and organic concentration exhibit definite relationships with the substrate removal rate and efficiency, it can be shown that these two parameters act in combination to affect the substrate removal rate and efficiency. Therefore, hydraulic loading alone does not determine the efficiency of the rotating biological contactor's performance correctly.

3.2 Effect of Organic Loading

In figure (6), the effect of these two parameters, i.e., flow rate and organic concentration, acting in combination is represented. The curve is drawn depending on the results of three experiments that are carried out at various organic concentrations and flow rates, but with approximately similar organic loading (17.0 g/m².d). As noted, there is no important difference between these plots. However, such results prove that the performance efficiency of a rotating biological

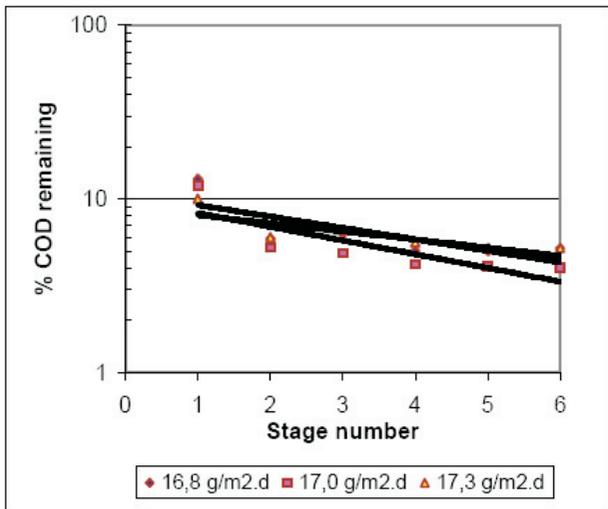


Fig. 6 Percent COD remaining per stage at various organic concentrations and flow rate but with constant organic loadings.

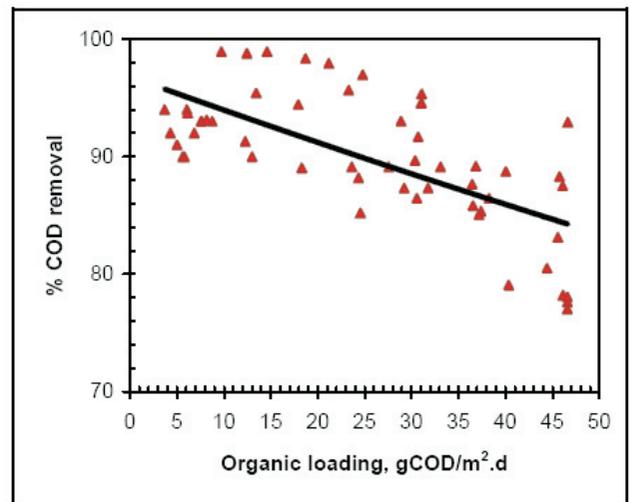


Fig. 8 Effect of organic loading on the COD removal efficiency under loading < 50 g COD/m².d.

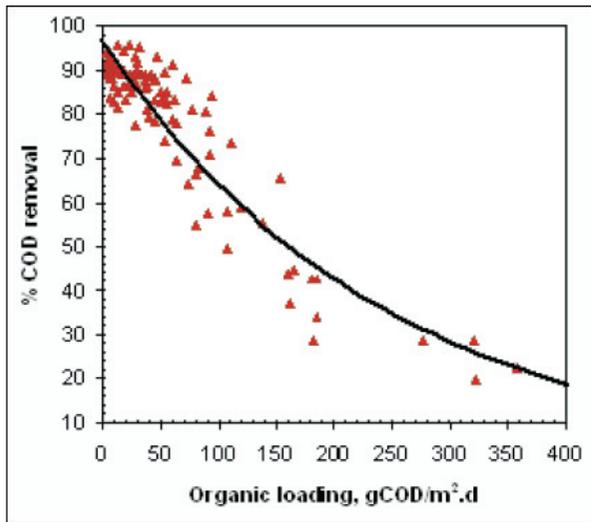


Fig. 7 Effect of organic loading on the COD removal efficiency.

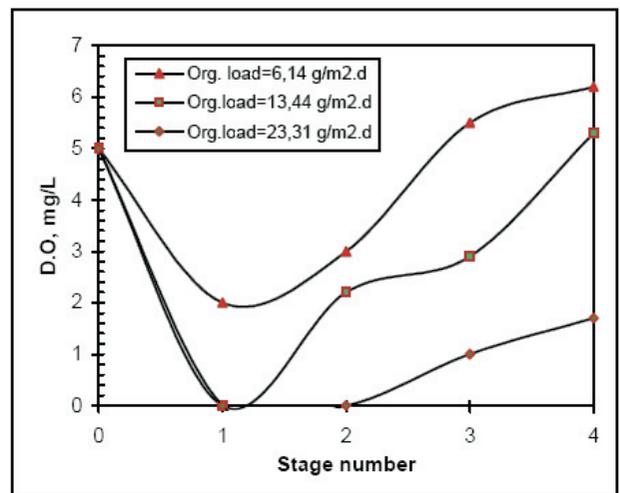


Fig. 9 Effect of organic loading on the dissolved oxygen concentration in the RBC stages (rotational velocity = 10rpm).

contactor is mainly dependent on organic loading rather than on the organic concentration or flow rate individually.

In figure (7), the effect of organic loading on the removal efficiency of the system is represented. As shown in the figure, there is a strong correlation between these two parameters ($R^2 > 90\%$). Increasing organic loading scientifically decreases the removal efficiency of the system.

Because rotating biological contactor systems are usually working at a low loading condition (up to 50 gCOD/m².d), the effect of

this range of loading on the removal efficiency is represented in figure (8).

In figure (9), the effect, both of organic loading and the stage number on the level of the dissolved oxygen concentration (DO) in the system basins, is drawn. As shown in the figure, dissolved oxygen profiles generally follow a pattern of rapid initial decline in the first stages and slow recovery in successive stages. As noted, there is a direct correlation between the dissolved oxygen concentration and

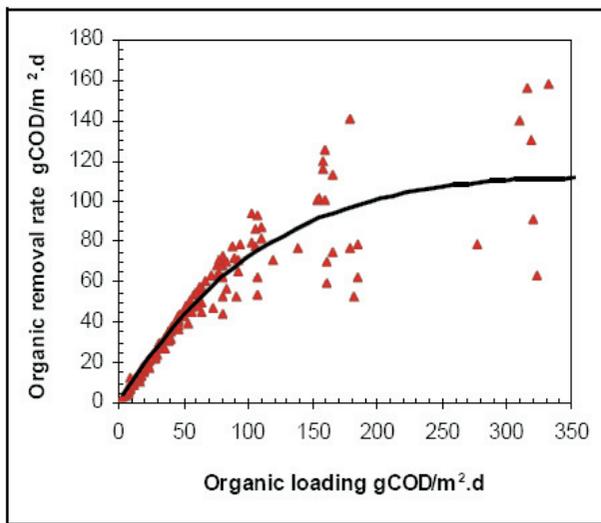


Fig. 10 Effect of total applied organic loading on organic removal rate under various operational conditions.

organic loading. A higher loading causes a sharp decrease in DO. Such a phenomenon can be explained by the heterotrophic uptake of dissolved oxygen in these stages. At the first and second stages, a high concentration of organic substrate is available, and then high utilization of the substrate and heterotrophic growth is attained, i.e., the maximum consumption of oxygen. As the organic substrate is metabolized through the successive stages, heterotrophic growth decreases, resulting in a decrease of the oxygen demand in the last stages. Where the organic substrate is low and heterotrophic growth is minimal, aeration provided by the contactor rotation supplied oxygen is in excess of demand.

In figure (10), the relationship between the organic loading applied and the removal of the organic loading in terms of (g CODremoved/m².d) is presented. As noted, there is a strong correlation between these two factors, especially at a range of loadings up to 150 g/m².d; after that, more scatter in the data is noted. However, to achieve an accepted level of removal from the figure, the system should be operated at a loading rate of not more than (100 gCOD/m².d).

4. CONCLUSION

Based on Monod kinetics and substrate inhibition kinetics for the biofilm, a model for the substrate removal efficiency of a 6 stage biofilm reactor was then established. The effect of the feeding rate, hydraulic loading and organic loading rate, in other words, the hydraulic retention time, was discussed. In addition, the effect of the influent substrate concentration was also investigated. The majority of COD removal occurs in the first stages of rotating biological contactor systems. The COD removal in the first stages ranges between (40-85%), depending on the organic loading applied. However, each type of wastewater and flow rate is also influenced by the system's efficiency, but their impact can be combined by the effect of organic loading. There is a strong correlation between the organic loading applied and the concentration of the suspended solids present in the rotating biological contactor basins. At higher loadings, a higher concentration is noted. At a loading of about (24 g/m².d), the suspended solids were 225, 125, 35, and 25 mg/L at the first, second, third and fourth stages respectively. To achieve an effluent quality of BOD < 25 mg/L, COD < 60 mg/L, the system should be operated at organic loading rates of (22 g BOD /m².d and 65 g COD g/m².d) respectively. The substrate utilization rate (organic removal rate) increases by increasing the organic loading to such a limit which after it, increasing the load has little or no impact on the removal rate. For rotating biological contactor systems that treat domestic wastewater, the value of organic loading at which the maximum removal rate is obtained was (150 g/m².d). The volumetric and surface removal rates which correspond to this load were (320 g COD/m³.d) and (100 g COD/m².d) respectively.

