BIOLOGICAL TREATMENT OF HIGH STRENGTH WASTEWATER IN A ROTATING PERFORATED TUBES BIOFILM REACTOR

by
Serkan EKER

January, 2002
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A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of
Dokuz Eylül University
In Partial Fulfillment of the Requirements for
the Degree of Master of Science in Environmental Engineering,
Environmental Science Program

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M.Sc THESIS EXAMINATION RESULT FORM

We certify that we have read this thesis and **"Biological Treatment of High Strength Wastewater in a Rotating Perforated Tubes Biofilm Reactor"** completed by **Serkan EKER** under supervision of **Prof.Dr. Fikret KARGI** and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Prof.Dr. Fikret Kargı

Supervisor

Prof. Dr. Orhan Uslu

(Committee Member)

Prof.Dr. Mithat Yüksel

(Committee Member)

Approved by the

Graduate School of Natural and Applied Sciences

Prof.Dr. Cahit HELVACI

Director

ACKNOWLEDGMENTS

I would like to thank my supervisor Prof. Dr. Fikret KARGI for his guidance motivation and valuable advises during my studies.

This study was supported by the research funds of Dokuz Eylul University, Izmir, TURKEY.

Env.Eng

Serkan EKER

ABSTRACT

A novel biofilm reactor named as 'rotating perforated tubes biofilm reactor (RPT)' was used for treatment of synthetic wastewater with and without liquid phase aeration. Also a rotating bio-disc (RBD) system was operated under the same conditions as that of the RPT, in order to compare the performances of both reactors under the same operating conditions such as influent COD concentration and A/Q ratio (A=1.34 m^2). The effects of major process variables such as feed wastewater flow rate, COD concentration and COD loading rate, liquid phase aeration, rotational speed of tubes and number of tubes on COD removal performances of both reactors were evaluated.

Rotating perforated tubes biofilm reactor consists of two stages each containing 25 perforated tubes mounted on vertical discs. The discs containing the battery of tubes were rotated by using a motor and a shaft passing through the central hole on the discs. Organisms grow in form of biofilm on inner and outer surfaces of the tubes during rotation of tubes. The holes on surfaces of the tubes help the biofilm organisms on inner surface of the tubes to be exposed to air more effectively. The outer surfaces of the tubes were rough to facilitate biofilm formation. Due to immersion of all tubes in wastewater and better mixing in liquid phase, RPT is more advantageous as compared to classical rotating biodiscs.

Liquid phase aeration was proven to be advantageous especially for high strength wastewaters at high COD loading rates. COD removal efficiency increased with increasing A/Q ratio and rotational speed of the tubes, but decreases with increasing feed COD and COD loading rate. Rotating perforated tubes biofilm reactor was found to be more advantageous as compared to rotating biodisc system resulting in

higher COD removal efficiencies especially at low A/Q ratio and high COD loading rates.

Kinetics of COD removal were investigated and kinetic constants were determined for both reactors. Empirical design equations were developed to describe the systems' performance as a function of major process variables such as A/Q ratio and feed COD content.

ÖZET

Yeni bir biyofilm reaktörü olan dönen delikli borular biyofilm reaktörü (DBBR) sıvı fazın havalandırmalı ve havalandırmasız olduğu durumlarda sentetik atıksuların arıtımında kullanılmıştır. Dönen delikli borular biyofilm reaktörünü dönen biyodisk reaktörü ile karşılaştırabilmek için dönen biyodisk reaktörü, aynı A/Q oranı (A=1.34 m^2) ve giriş KOİ derişimi gibi işletme şartlarında işletildi. Temel proses değişkenleri olan giriş KOİ derişimi, A/Q oranı, KOI yükleme hızı, sıvı fazın havalandırılması, boruların dönme hızı, boruların sayısı gibi parametrelerin KOİ giderim verimine ve hızına olan etkileri incelendi.

Dönen delikli borular biofilm reaktörü iki kısımdan oluşmakta ve her kısım düşey disklere yerleştirilmiş 25 delikli boru (toplam 50) içermektedir. Disklerin ortasından şaft geçmekte ve borular şaftın bağlı olduğu bir motor yardımıyla döndürülmektedir. Organizmalar dönme sırasında boruların hem iç yüzeyinde hem de dış yüzeyinde biyofilm tabakası oluşturmaktadır. Boruların üzerindeki delikler, boruların iç yüzeyinde oluşan biofilm organizmalarının hava ile temasını sağlamaktadır. Boruların dış yüzeyi biofilm oluşumunu kolaylaştırmak için pürüzlüdür. Boruların tamamının atıksu içerisine batması ve sıvı fazda daha etkili bir karışma olmasından dolayı klasik dönen biyodisk reaktöre kıyasla daha avantajlıdır.

Sıvı fazı havalandırmanın, özellikle yüksek KOİ yükleme hızlarında atıksudan KOİ giderimi için etkili olduğu bulundu. KOI giderim verimi artan A/Q oranı ve boruların dönme hızı ile arttı, ancak, artan giriş KOI derişimi ve KOI yükleme hızı ile düştü. Dönen delikli borular biofilm reaktörü KOİ giderim verimleri, aynı şartlarda dönen biyodisk sistemiyle karşılaştırıldığında özellikle düşük A/Q oranı ve yüksek KOI yükleme hızlarında daha avantajlı olduğu bulundu.

Her iki reaktor için KOİ giderim kinetikleri araştırıldı ve deneysel veriler kullanılarak kinetic sabitler bulundu. Temel proses değişkenleri olan A/Q oranı ve giriş KOİ içeriğinin bir fonksiyonu olarak sistemin KOI giderim performansını belirleyen matematiksel tasarım eşitlikleri geliştirildi.

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CHAPTER ONE
INTRODUCTION

1.1. INTRODUCTION

Rotating biodisc contactors has been the most widely used type of rotating biofilm contactors. The rotating biological disc (RBD) is an attached biofilm system which typically consists of series circular discs mounted on a horizontal shaft and rotated by a motor. Many types of proprietary RBD systems have been developed. RBD's were commonly used in wastewater treatment, since they offer several advantages over other biofilm reactors such as trickling (downflow) and upflow biological filters and fluidized beds. Control of the environmental conditions and the biofilm thickness is easier in rotating biofilm discs, since the liquid phase is more homogenous; the biofilm is visible and reachable during the operation as compared to the biological filters. Aeration is much more effective in rotating biodiscs as a result of direct contact of biofilm and air during rotation. For the treatment of high strength wastewater, gentle aeration of liquid phase was shown to improve the COD removal performance of the system (Kargi, 1997). In addition to some mechanical problems associated with the use of rotating biodiscs, insufficient mixing in the liquid phase, falling off the biofilm from disc surfaces during operation and limited surface area of discs for biofilm formation due to 40% immersion in wastewater can be mentioned as disadvantages of rotating biodisc systems.

Modifications of rotating biodisc contactors were developed to overcome some of the aforementioned disadvantages such as addition of wings and use of porous disc surfaces. In order to overcome some of the problems associated with rotating biodiscs, a novel biofilm contactor called 'rotating perforated tubes or pipes biofilm reactor' was developed in this study.

Rotating biological contactors were widely used in biological treatment of wastewater for COD/BOD removal (Clark, 1978; Andreadakis, 1987; Fujie, 1983; Pan, 1992; Poon, 1979; Wilson, 1980, 1993; Kargi, 1999) and nitrification/ denitrification (Wu, 1981; Poon, 1981; Watanabe, 1985; Gönenç, 1985; Hing, 1976) purposes. Diffusion limitations and COD removal kinetics coupled with diffusion of nutrients in biofilm reactors such as rotating discs were investigated by many researchers (Kornegay, 1968; La Motta, 1976; Rittmann, 1980; Shieh, 1982; Trulear, 1982; Williamson, 1976; Atkinson, 1974).

Effects of various operating parameters such as hydraulic residence time or A/Q ratio (Kargı, 1997; Kugaprasatham et al., 1991), organic loading rate, liquid phase aeration (Kargı, 1997), disc rotational speed (Friedman et al., 1979) on performance of rotating biodiscs have been studied.

Liquid phase aeration in RBC systems is not common in practice. Almost all RBC operations are performed without liquid phase aeration resulting in dissolved oxygen limitations in liquid phase at high organic loading rates. Use of supplemental liquid phase aeration in RBC's was shown to improve the COD removal rate in one reported study (Surampalli&Baumann, 1993). The overall performance of RBCs receiving supplemental aeration was significantly better with respect to COD removal efficiency than the RBCs without supplemental air. (Surampalli&Baumann, 1995)

Several studies have reported problems with initial stages of RBC systems reflected by heavy biofilm growth, the presence of nuisance organisms, such as beggiatoa, and a reduction in organic removal rates. These problems have been attributed to excessive organic loadings resulting in low dissolved oxygen conditions. (Chesner& Molof, 1977; Hitdlebaugh& Miller, 1981)

Surampalli and Baumann (1987) used the first order model to describe performance of RBC reactor under high concentration of dissolved oxygen. Other authors used first order kinetics on RBC reactor in order to minimize the disc area required by RBC. (Fujie *et al*, 1983; Leduc& Buchanan, 1993).

Wilson (1993) reviewed RBCs described by first and zero order kinetics but other kinetic models such as the half-order kinetics have also been proposed (Shiek, 1982; Arvin&Harremoes, 1990) as well as more complex models such as those presented for multi-staged RBC's by Pano&Middlebrooks (1983) and Bunchanan&Leduc (1994). References using Monod kinetics for modeling RBC's are also quite frequent (Kornegay&Andrews, 1968; Clark *et al*, 1978).

In order to overcome some of the problems associated with rotating biodiscs a new biofilm reactor called 'Rotating perforated tubes biofilm reactor' was developed. The rotating perforated tubes biofilm (RPT) reactor consists of a battery of perforated tubes mounted on perforated discs through the holes on the discs. The shaft and the tubes are rotated with the aid of a motor. The battery of the tubes is immersed in the wastewater tank during rotation. Organisms grow in form of biofilm on the inner and outer surfaces of the tubes. Aeration is provided by direct contact of the biofilm organisms with air during rotation.

The rotating perforated tubes biofilm reactor was used for treatment of synthetic wastewater of different strength with and without liquid phase aeration. Effects of important process variables such as feed COD concentration, COD loading rate, feed flow rate, rotational speed, number of tubes and liquid phase aeration on the system's performance were investigated. In addition all experiments were repeated by using rotating biodisc reactor under the same conditions in order to compare the performances of both reactors.

Kinetics of COD removal from the wastewater was investigated and kinetic constants were determined by using the experimental data. Empirical design equations were developed to estimate COD removal efficiency as a function of A/Q ratio and feed COD content for both reactors.

1.2. Objectives and Scope

Major objectives of this thesis can be summarized as follows;

- to develop a new biofilm reactor consisting of rotating perforated tubes for wastewater treatment as an alternative to rotating biodisc systems
- to investigate COD removal performance of the novel biofilm reactor named as 'rotating perforated tubes biofilm reactor (RPT)'.
- to enhance biological treatment efficiency of high strength wastewater by liquid phase aeration.
- to compare performances of RBD and RPT reactors for treatment of different strength synthetic wastewaters under the same experimental conditions.
- to determine the effects of important process variables such A/Q ratio, feed COD concentration, COD loading rate, rotational speed of perforated tubes, number of tubes on COD removal efficiency.
- to develop mathematical models describing systems' performance for both RPT and RBD systems.
- to determine kinetic constants by using experimental data.

In the first part of the thesis, rotating perforated tubes biofilm reactor's COD removal efficiency was studied without liquid phase aeration. Effects of important processes variables such as A/Q ratio and feed COD concentrations and COD loading rate on COD removal efficiency were investigated. Kinetic constants were determined by using experimental data without liquid phase aeration and an empirical mathematical model was developed. Effects of the number (surface area) and rotational speed of the tubes on COD removal performance was also investigated without liquid phase aeration.

In the second part of the thesis, system was studied with liquid phase aeration. Effects of major process variables such as feed wastewater flow rate, COD concentration and loading rate on the rate and extent of COD removal were investigated. An empirical design equation was developed to describe the system's performance with liquid phase aeration.

In the third part of the thesis, rotating bio-disc reactor was used without liquid phase aeration under the same conditions as that of the RPT, such as the same feed COD concentration, A/Q ratio and other environmental conditions in order to compare the performance with that of the RPT. Effects of process variables on COD removal efficiency and the rate were investigated. Kinetic constants were determined by using experimental data without liquid phase aeration. An empirical mathematical model was developed.

CHAPTER TWO

MATERIALS AND METHODS

2.1 Experimental setup

Figure 2.1.1 depicts a schematic of the rotating perforated tubes biofilm reactor. The system consists of a feed reservoir, wastewater tank containing battery of rotating tubes, driving motor, shaft and wastewater pump. Feed reservoir was placed in a deep refrigerator to keep the temperature below 5 C in order to avoid any decomposition. The rotating tube system had two sections mounted on the same shaft each having 25 perforated tubes (total of 50 tubes) made of PVC. Outer and inner diameter of the tubes were D_o = 2.1 cm and D_i = 1.3 cm resulting in a total surface area of A = 1.34 m^2. Each tube had twenty holes of 0.5 cm in diameter on their surfaces, which would allow air passage to the inner surface of the tubes. The tubes were completely immersed in the semi cylindrical tank with a length of 60 cm, diameter of 30 cm and depth of 18 cm. The tubes were located on the peripheral area of the discs and were completely immersed in the wastewater in the tank. Total liquid volume in the tank was V_L = 9 L. Therefore, the biofilm area per unit wastewater volume in the tank was a = 149 m^2/m^3. Liquid phase aeration was accomplished by an air pump and perforated tubes/ diffusers located underneath the battery of tubes in the liquid phase. The discs were rotated with a constant speed of 5 rpm which was a typical value on the basis of literature reports. In some experiments, the rotational speed was changed between 3 and 12 rpm.

Figure 2.1.2 depicts a schematic of the rotating bio-disc (RBD) reactor. The RBD system consists of a feed reservoir, wastewater tank containing battery of rotating tubes, driving motor, shaft and wastewater pump. Feed reservoir was placed in a deep refrigerator to keep the temperature below 5 ^{0}C in order to avoid any decomposition.

The rotating bio-disc reactor contained only biodiscs mounted on a shaft through the central hole. The system had two sections containing 11 discs of diameter D_o= 20 cm in each (total of 22 discs) resulting in a total disc surface area of A = 1.38 m^2. Discs were made of polypropylene and were 40% immersed in water; however, the whole surface area of the discs was covered by biomass. Total liquid volume in aeration tank was V_L =9 L resulting in biodisc surface area per unit reactor volume of a = 153 m^2/m^3. Discs were rotated with a constant speed of n=5 rpm with a driving motor. Total disc surface area was approximately equal to the total tubes surface area in RPT.

2.2. Wastewater Composition

Synthetic wastewater used throughout the studies was composed of diluted molasses, urea, KH_2PO_4 and $MgSO_4$ resulting in COD/N/P = 100/10/1.5 in the feed. COD concentration in the feed was varied between COD_o = 1,000-11,000 mg/L and COD/N/P ratio was kept constant throughout the experiments. Feed COD concentration in experiments with variable flow rate was approximately 2,000 ± 200 mg/L. $MgSO_4$ concentration in the feed was 50 mg/L in all experiments. pH of the feed media was 6.9 and increased up to pH = 7.9 in the treatment tank as a result of ammonia release from hydrolysis of urea.

2.3. Organisms

The activated sludge culture used as inoculum was obtained from Pınar Meat Industry wastewater treatment plant located in Izmir, Turkey. This culture was cultivated in the laboratory on a shaker by using the same media and was used for the inoculation of the system.

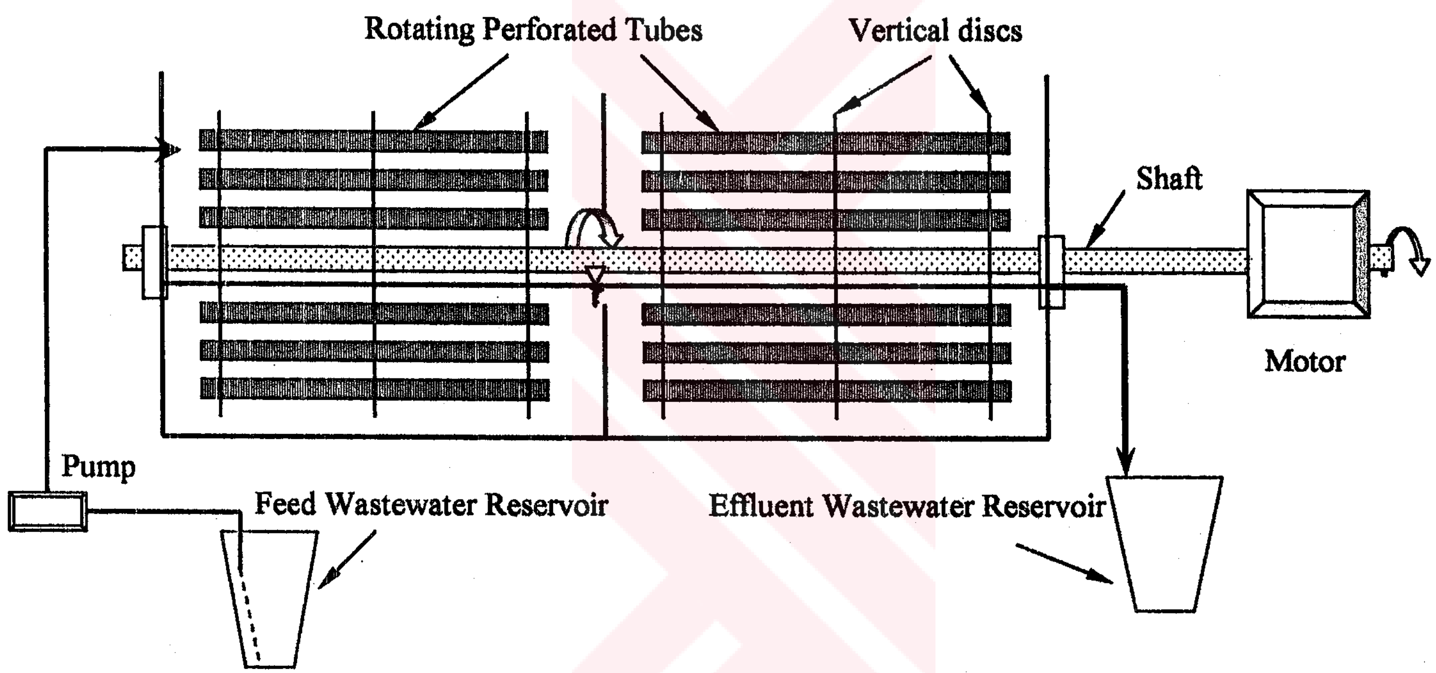

Figure 2.1.1 Schematic Diagram for Rotating Perforated Tubes Biofilm Reactor

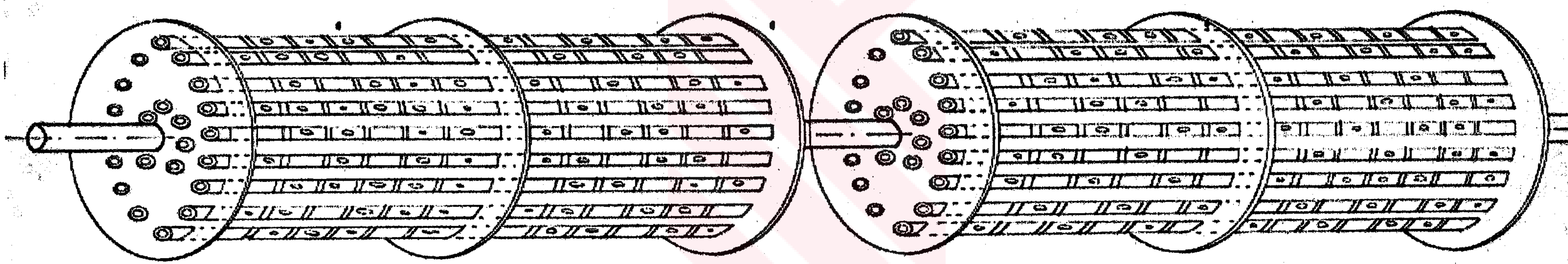

Figure 2.1.1.b Technical drawing of the rotating perforated tubes biofilm reactor (RPT)

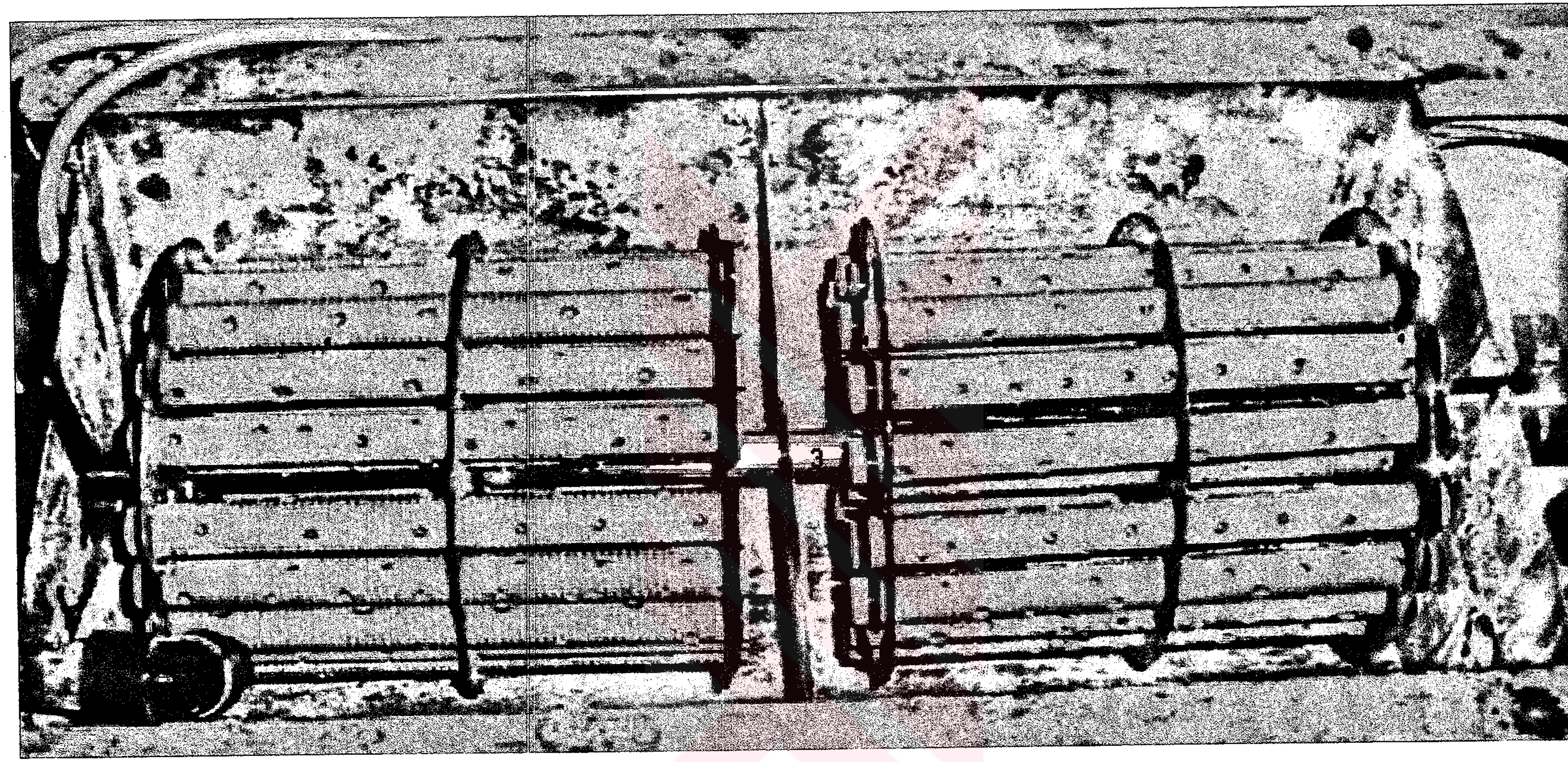

Figure 2.1.1.c A photograph of the rotating perforated tubes biofilm reactor (RPT)

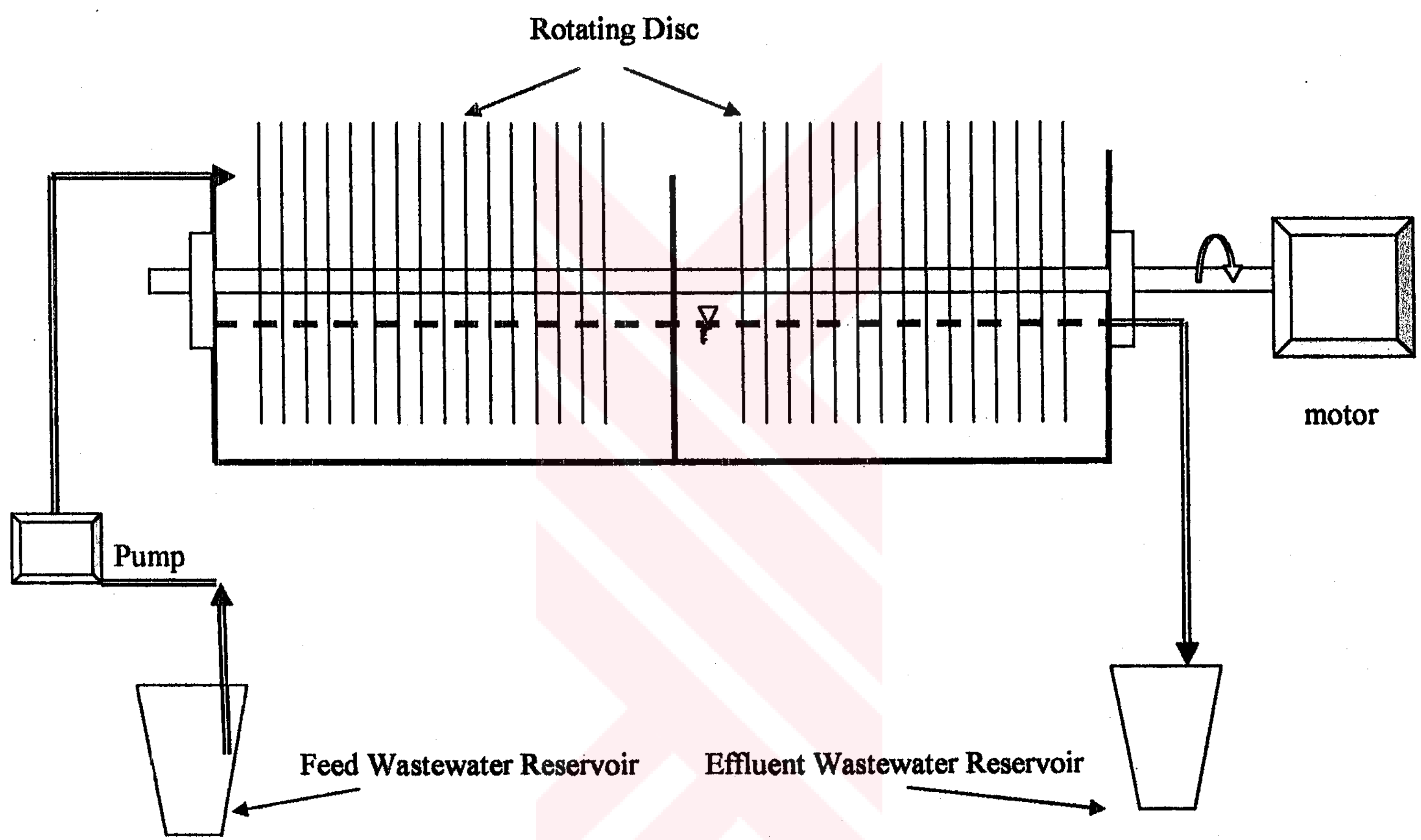

Figure 2.1.2 Schematic Diagram of Rotating Bio-disc Reactor

2.4. Experimental Procedure

Experiments were started batch wise for both studies. About 9L of the synthetic wastewater was placed in the treatment tank containing support materials (perforated tubes for RPT experiments/discs for RBD experiments) and was inoculated with the activated sludge culture. RPT and RBD systems were operated batch wise by changing the media in every three days until significant biofilm was developed on the surfaces of the tubes or discs. The batch operation usually took about two weeks to obtain a biofilm thickness of about 1-1.5 mm. During continuous operation feed was provided from one end and was removed from the other end of the tank. Temperature and pH were approximately T = 20 ± 2 C and pH = 7.5± 0.3 during operation. pH was controlled around 7.5 by manual addition of dilute sulfuric acid twice a day. Experiments were conducted with and without liquid phase aeration. Biofilm thickness was controlled around 1.5 mm by manual removal of thick biofilm from surfaces of the tubes. The system was operated at steady- state at least for five days for each experimental condition and the last three data points were considered in evaluations.

2.5. Analytical Methods

Samples were removed daily during steady-state operation from the feed reservoir and the effluent. In order to avoid any interference on COD measurements by organisms, the samples were centrifuged to remove the biomass (Kargi & Dinçer, 1999). Soluble COD measurements were made on clear supernatant according to the Standard Methods (1989). Average of the last three steady-state measurements were used in data analysis with standard deviations of less than 5%.

CHAPTER THREE

RESULTS AND DISCUSSION

3.1. Performance of Rotating Perforated Tubes Biofilm Reactor without Liquid Phase Aeration

Four sets of experiments were performed. Feed flow rate was changed to yield θ_H =2-10 h in the first set of experiments, while the feed COD was approximately constant around 2,000 ± 200 mg/L. Feed COD content was changed between 1,000 mg/L and 11,000 mg/L in the second set of experiments, while the feed flow rate was kept constant to yield θ_H = 6 h. Rotational speed of perforated tubes was changed from 3 to 12 rpm in the third set of experiments while feed COD concentration and feed flow rate were constant. In the fourth set of experiments, number of perforated tubes (surface area) was changed between 14 and 50.

3.1.1. Experiments with Different Feed Flow Rates

The major goal in this set of experiments was to investigate the system's COD removal performance at different A/Q ratios while the feed COD was kept approximately constant around 2,000 ± 200 mg/ L.

Figure 3.1.1 depicts variation of effluent COD and COD removal efficiency (E) with A/Q ratio. The effluent COD decreased and COD removal efficiency increased with increasing A/Q ratio. In order to obtain COD removal efficiency (E) larger than 95%, the A/Q ratio should be larger than 1,200 $m^2.h/ m^3$.

Figure 3.1.2 depicts variation of COD removal rate ($R_s = Q (S_o- S) / A$) with A/Q ratio. The rate decreased with increasing A/Q ratio as a result of decreasing flow rate

(Q) at constant A and S_o. A fivefold decrease in A/Q (from 1500 to 300 $m^2.h / m^3$) resulted in the same degree of reduction in the rate (from 7500 to 1500 mg/ m^2.h).

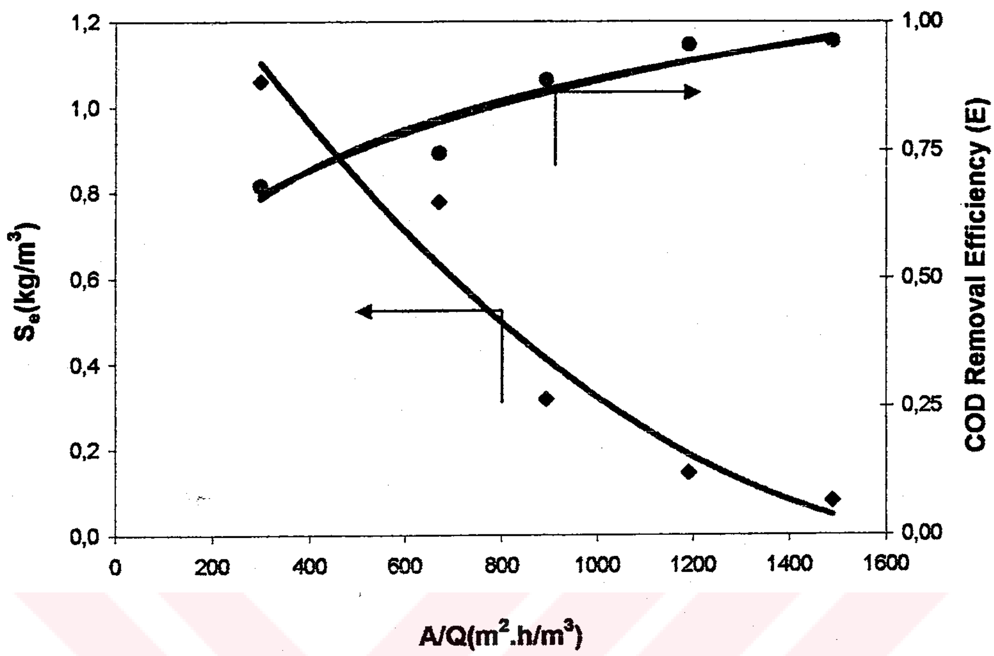

Figure 3.1.1 Effluent COD (S_e) and COD removal efficiency (E) as a function of A/Q ratio

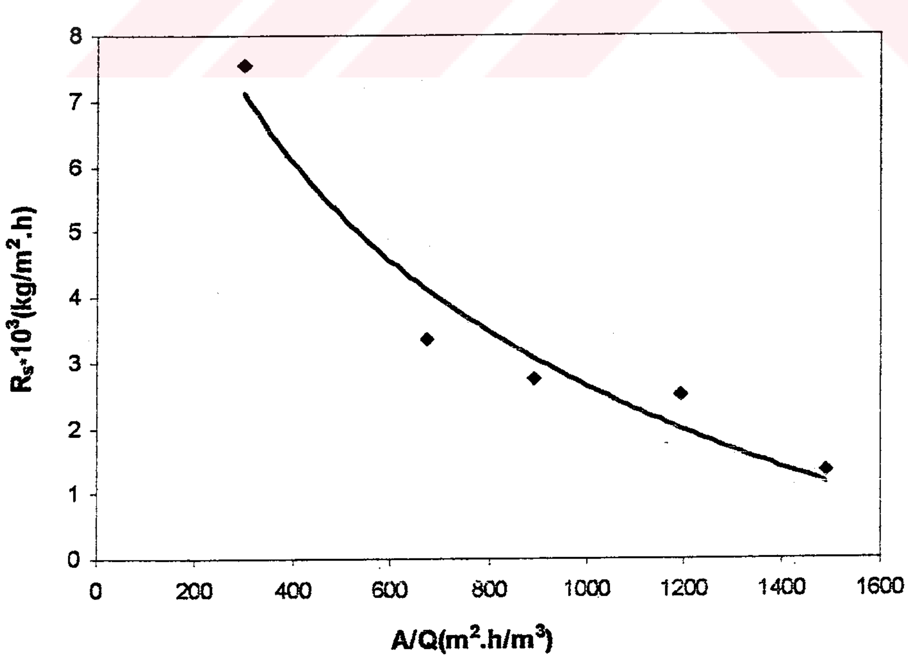

Figure 3.1.2 Variation of COD removal rate (R_s) with A/Q ratio

3.1.2. Experiments with Different Feed COD Concentrations

The objective of this set of experiments was to investigate the system performance at different organic loading rates per unit biofilm surface area ($L_s = Q.S_o/A$). Variations of the effluent COD concentration (S_e) and COD removal efficiency (E) with the feed COD concentration (S_o) are depicted in Figure 3.1.3. The effluent COD increased and COD removal efficiency decreased with increasing feed COD. This variation was more significant especially for feed COD values above 3,000 mg/L (3 kg/ m^3).

Variations of the effluent COD and COD removal efficiency with COD loading rate (L_s) are depicted in Figure 3.1.4. Increases in COD loading rate resulted in significant decreases in COD removal efficiency especially for L_s values above 3,000 mg/ m^2.h. COD loading rate should be kept below 3000 mg/ m^2.h for more than 90% COD removal.

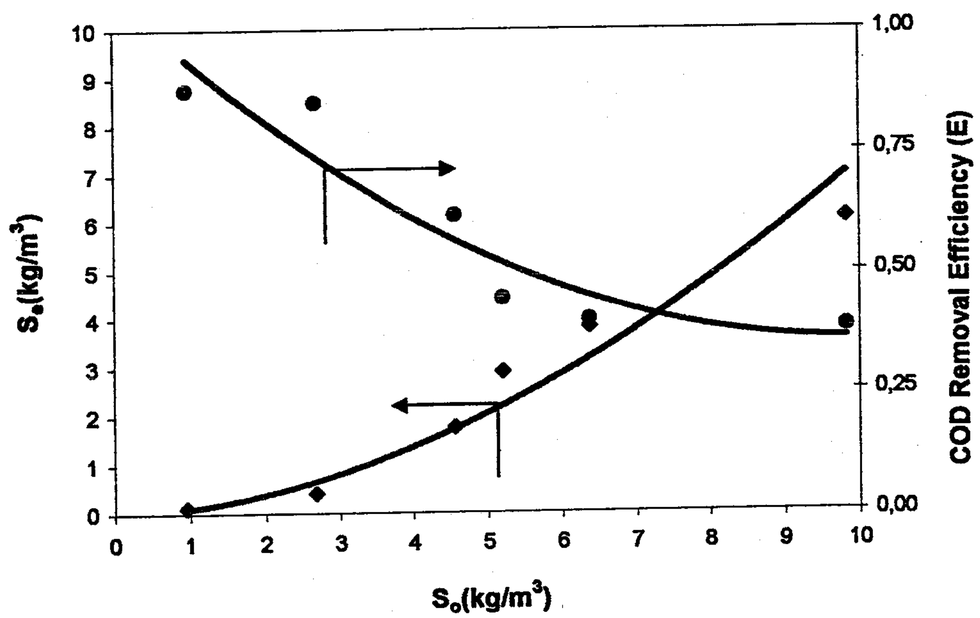

Figure 3.1.3 Variation of effluent COD (S_e) and COD removal efficiency (E) with the feed COD (S_o).

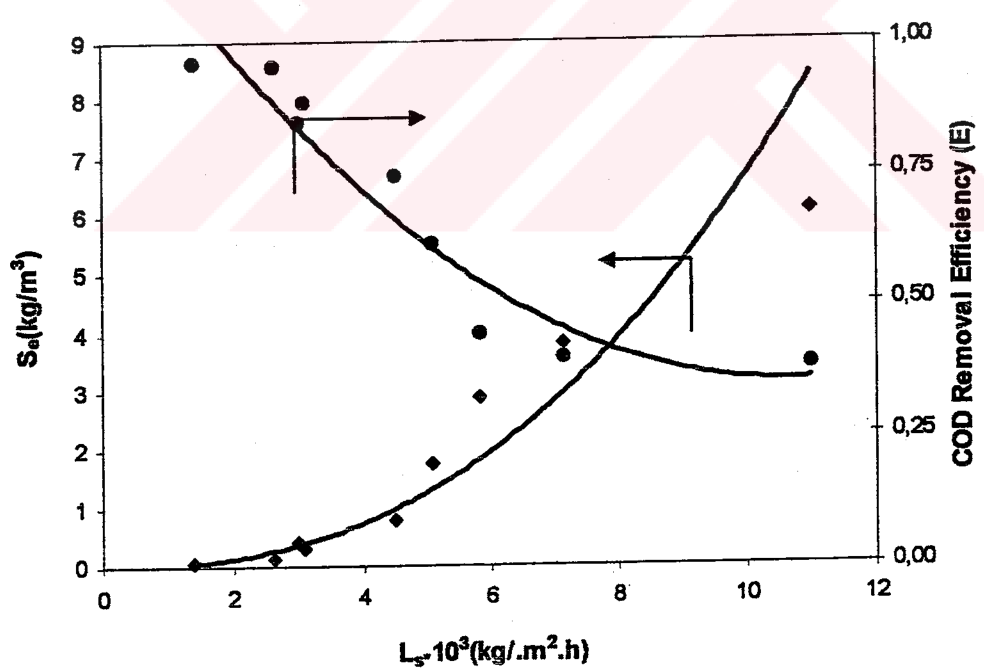

Figure 3.1.4 Variation of effluent COD (S_e) and COD removal efficiency (E) with COD loading rate.

3.1.3. Effects of Rotational Speed of Tubes on COD Removal

The effect of rotational speed of perforated tubes on COD removal efficiency and COD removal rate without liquid phase aeration were investigated. Rotational speed of perforated tubes was changed between 3 with 12 rpm while the feed COD concentration (S_o) was constant around 2,000 mg/L. Feed flow rate was also kept constant to yield θ_H= 6 h .

Figure.3.1.5. depicts variation of effluent COD concentration and COD removal efficiency with rotational speed of tubes. The effluent COD (S_e) decreased and COD removal efficiency (E) increased with increasing rotational speed (rpm).

Variations of COD removal rate (R_s) with rotational speed of perforated tubes (rpm) are shown in Figure 3.1.6. Increases in rotational speed of tubes resulted in increases in COD removal rate.

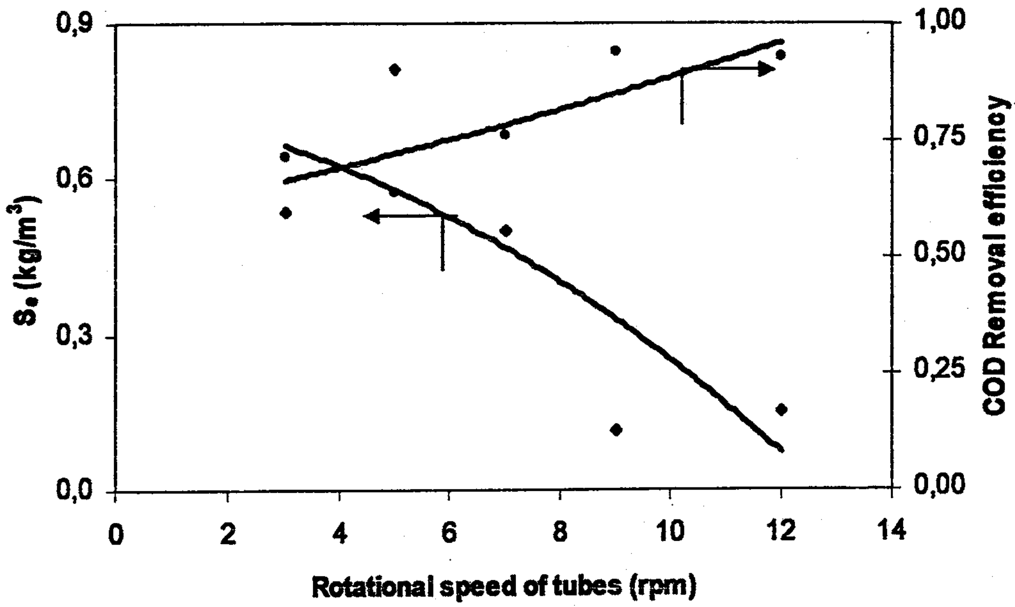

Figure 3.1.5 Effects of rotational speed of perforated tubes on COD removal efficiency and the effluent COD (S_e).

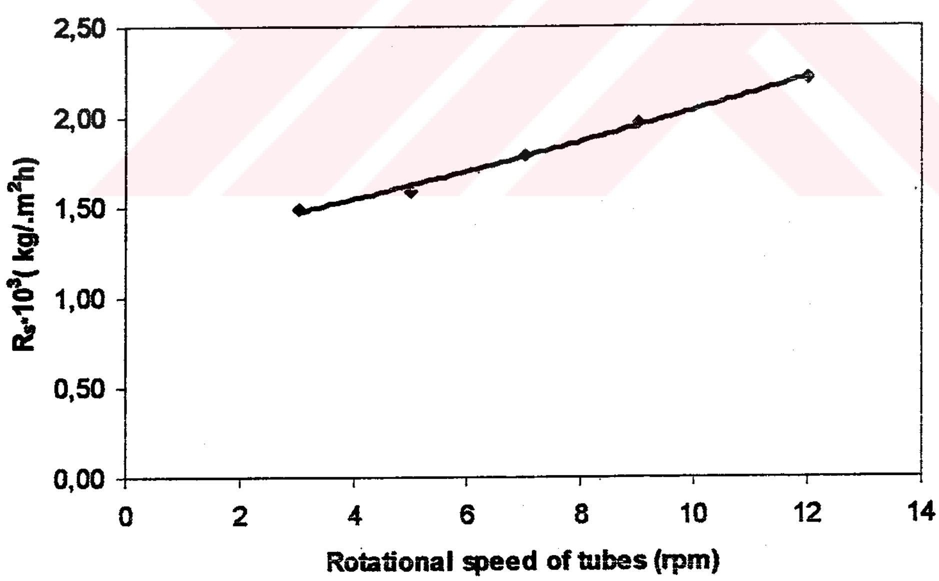

Figure 3.1.6. Variation of COD removal rate (R_s) with rotational speed of perforated tubes.

3.1.4. Effects of Number of Perforated Tubes on COD removal

The effects of number of perforated tubes (tube surface area) on COD removal efficiency and rate of COD removal without liquid phase aeration were investigated. The feed COD concentration was S_o= 2,000 mg/l and the hydraulic residence time was 6 h in all experiments.

RPT unit consisted of two stages containing 50 perforated tubes. Perforated tubes were equally removed from each stage during the experiments. The number of tubes were varied between 44 and 14 tubes.

Variation of effluent COD (S_e) and COD removal efficiency (E) with number of tubes are depicted in Figure 3.1.7.Feed COD concentration increased from S_e=500 mg/l with N=44 tubes to S_e=1290 mg/L with N=14 tubes. COD removal efficiency decreased with decreasing number of the perforated tubes from 76% (N=44) to 39% (N=14).

Figure 3.1.8 depicts variation of surface COD removal rate with the number of tubes. Surface COD removal rate (R_s) decreased with the increasing number of the tubes as a result of increasing tube surface area. Surface COD removal rate (R_s) with 44 tubes was 2.5 kg COD/m^2.h and which increased to 3.24 kg COD/m^2.h with 14 tubes.

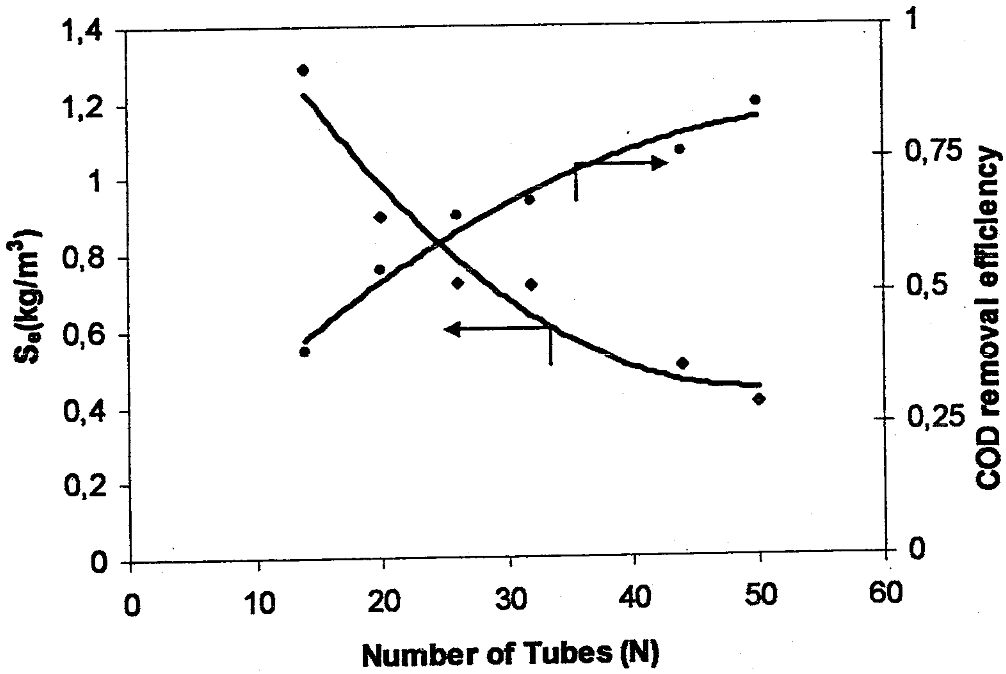

Figure 3.1.7 Variation of effluent COD (S_e) and COD removal efficiency with number of perforated tubes (surface area).

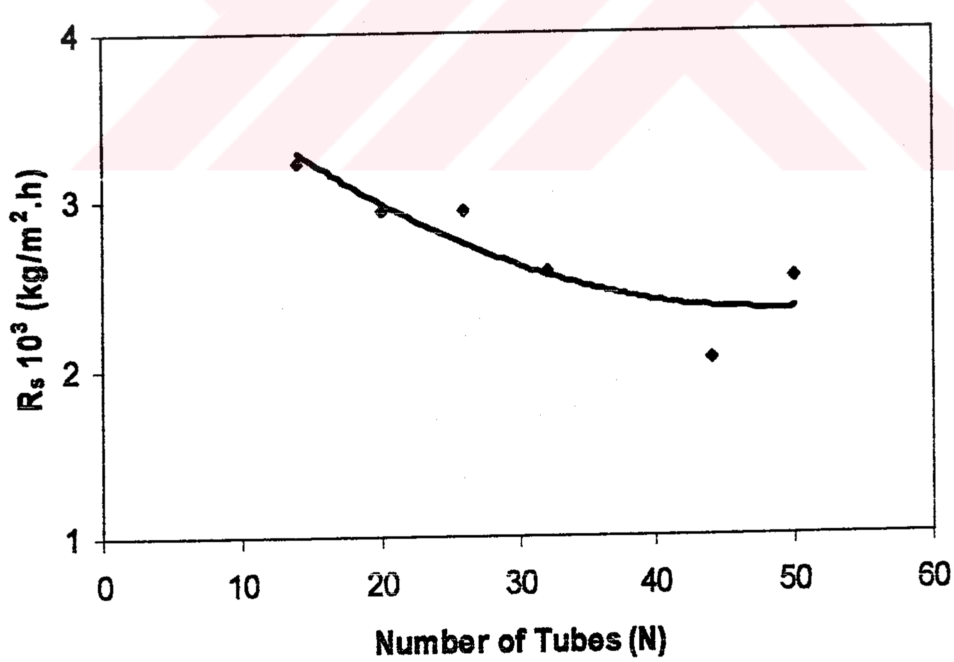

Figure 3.1.8 Variation of surface COD removal rate (R_s) with number of perforated tubes (surface area).

3.1.5. Kinetic Analysis of the System

Following kinetic model was proposed for COD removal from the wastewater by rotating perforated tubes biofilm reactor. By assuming a Monod type COD removal rate, a COD balance around the reactor yields the following equation:

$$Q\,(S_o - S) = \frac{k\,X\,S}{K_s + S}\,A = \frac{R_m\,S}{K_s + S}\,A \qquad (3.1)$$

or

$$\frac{Q\,(S_o - S)}{A} = R_s = \frac{k\,X\,S}{K_s + S} = \frac{R_m\,S}{K_s + S} \qquad (3.2)$$

where, Q is flow rate of the feed wastewater (m^3/h); So and S are the feed and effluent COD (kg/m^3); A is the total biofilm surface area (m^2); k is maximum COD removal rate constant (d^{-1}); X is the biomass concentration on the tube surfaces (kg/ m^2); K_s is the saturation constant (kg/m^3). Since the liquid phase in the tank was not aerated, suspended cell's concentration in the liquid phase was less than 500 mg/L. Therefore, suspended cell's contribution for COD removal was neglected. It was assumed that mainly biofilm organisms on the tube surfaces removed COD from the wastewater.

In double reciprocal form, eqn 3.2 may be written as,

$$\frac{1}{R_s} = \frac{A}{Q\,(S_o - S)} = \frac{1}{R_m} + \frac{K_s}{R_m}\,\frac{1}{S} \qquad (3.3)$$

A plot of $1/R_s$ versus $1/S$ yields a line, with a slope of K_s/R_m and an intercept of $1/R_m$.

Experimental data obtained with different flow rates at constant feed COD_o of 2,000 ± 200mg/L were plotted in form of A/Q.(So- S) versus 1/S and from the slope and intercept of the best-fit line the following values were found for R_m and K_s (Figure 3.1.9).

R_m =5.9x10^{-3} kg/ m^2.h =5900 mg/m^2.h and K_s = 260 mg/L = 0.26 kg/m^3, (R^2 =0.90)

Therefore, the rate eqn. may be written as,

$$R = \frac{R_m\ S}{K_s + S} = \frac{5,900\ S}{260 + S} \quad \text{where S is in mg/L and R is in mg/m}^2\text{.h} \qquad (3.4)$$

Typical biomass concentrations on tube surfaces and in liquid phase were X_f = 50 g/m^2 and X_s = 0.3 g/L resulting in total amount of biomass in biofilm and in liquid phase as X_{TF} = 67 g and X_{TS} = 2.7 g, respectively. Therefore, COD removal by suspended cells can be neglected as compared to that of the biofilm. From the definition of R_m = k X_f, the maximum COD removal rate constant was found as k = 0.12 h^{-1} = 2.9 d^{-1}.

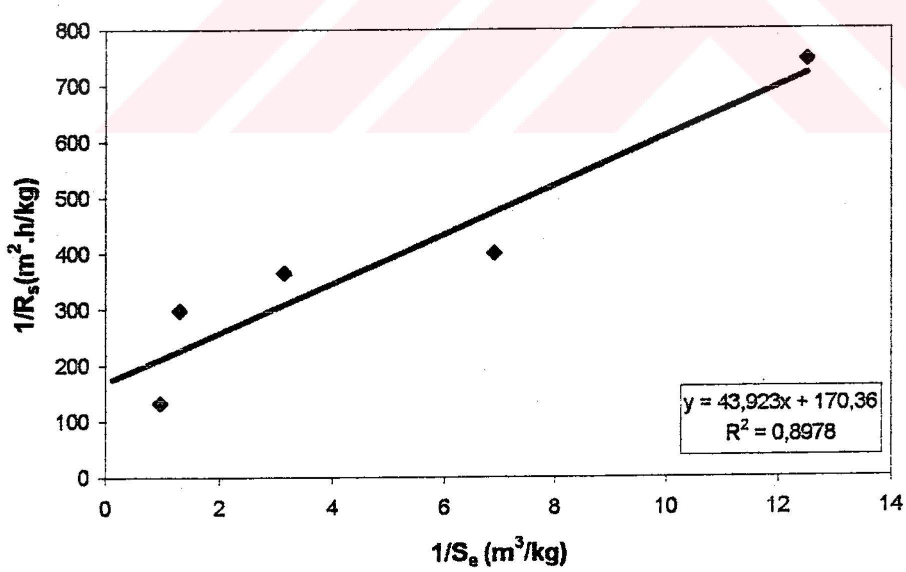

Figure 3.1.9 Double reciprocal plot of $1/R_s$ versus 1/S for determination of the kinetic constants

3.1.6. Empirical Model Development

An empirical model describing the COD removal efficiency as a function of A/Q ratio and feed COD concentration was developed. The model has the following form:

$$E = 1 - \frac{S}{S_o} = a\,(A/Q)^{b} \cdot S_o^{c} \qquad (3.5)$$

In linearized form this eqn.may be written as

$$\text{Ln}\, E = \text{Ln}\, a + b\, \text{Ln}\, (A/Q) + c\, \text{Ln}\, S_o \qquad (3.6)$$

Experimental data were obtained at constant feed COD of approximately, S_o=2,000 mg/L and at different A/Q ratios. The data were plotted in form of Ln E versus Ln (A/Q) and from the slope of the best-fit line the exponent b was found as b = 0.24 (R^2= 0.90).

Similarly, experimental data obtained at different feed COD (1,000- 11,000 mg/L) and constant A/Q of 894 $m^2.h/m^3$ were plotted in form of Ln E versus Ln S_o. From the slope of the best fit line the exponent c was found as c = - 0.2 (R^2 = 0.93). Also, from the intercept of the aforementioned plots the coefficient 'a' was found as a = 0.21.

Therefore, the empirical eqn would have the following form,

$$E = 0.21\,(A/Q)^{0.24}\ S_o^{-0.2} \qquad (3.7)$$

COD removal efficiency of the system can be estimated by using eqn 3.7 for different operating conditions.

3.2. Performance of Rotating Perforated Tubes Biofilm Reactor with Liquid Phase Aeration

Two sets of experiments were performed with liquid phase aeration. In the first set of experiments, feed flow rate was changed while the feed COD_o was approximately constant around 2,000 mg/L. Feed COD content was changed between 1,000 mg/L and 11,000 mg/L in the second set of experiments, while the feed flow rate was kept constant to yield $\theta_H = 6$ h..

3.2.1 Experiments with Different Feed Flow Rates

Figure 3.2.1 depicts variation of effluent COD and COD removal efficiency with A/Q ratio for both cases. Effluent COD decreased and COD removal efficiency increased with increasing A/Q ratio for both aerated and unaerated liquid phase. Effluent COD levels obtained with liquid phase aeration were somewhat lower than those obtained in the absence of aeration. However, the difference between the two cases was not that significant since the feed COD was low as 2000 mg/L. In order to obtain COD removal efficiencies of larger than 90%, A/Q ratio must be larger than 1200 $m^2.h/m^3$ for both cases.

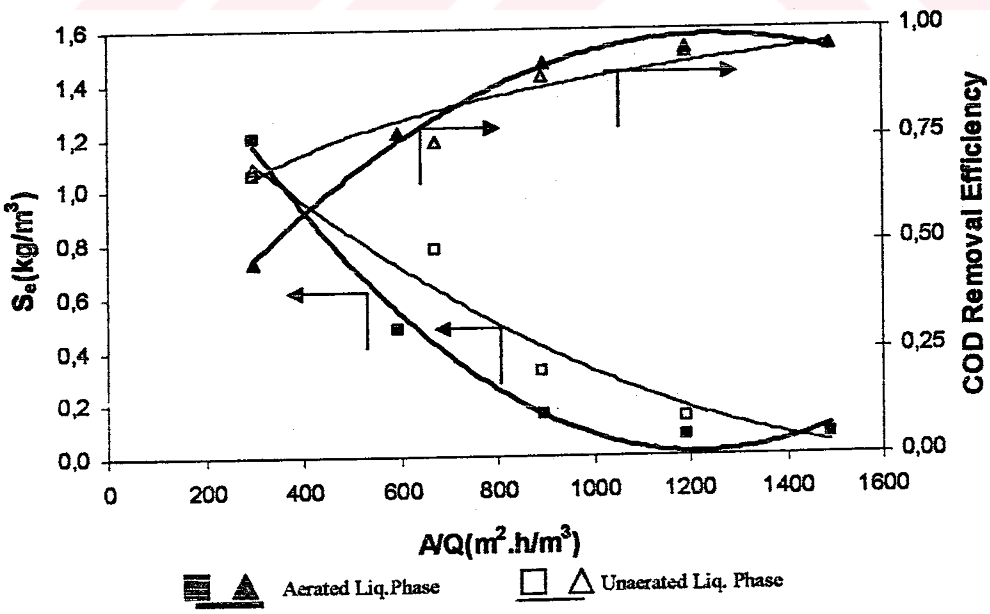

Figure 3.2.1 Effluent COD and COD removal efficiency as a function of A/Q ratio

3.2.2. Experiments with Different Feed COD Concentrations

The objective of this set of experiments was to investigate the system performance at different COD loading rates per unit biofilm surface area ($L_s = Q\ S_o\ /\ A$). Variations of the effluent COD concentration and COD removal efficiency with the feed COD content are depicted in Figure 3.2.2, with and without liquid phase aeration. The effluent COD increased and COD removal efficiency decreased with increasing feed COD. This variation was more significant especially for feed COD of above 3,000 mg/L (3 kg/ m^3). Liquid phase aeration was proven to be significantly advantageous especially for high strength wastewaters of CODo >3,000 mg/ L resulting in lower effluent COD levels or higher COD removal efficiencies as compared to the results of unaerated liquid phase.

Variations of the effluent COD and COD removal efficiency with COD loading rate (L_s) are depicted in Figure 3.2.3. Increasing COD loading rate resulted in significant decreases in COD removal efficiency especially for L_s values above 3,000 mg/ m^2.h.. COD loading rate should be kept below $L_s < 3000$ mg/ m^2.h for more than 90% COD removal in the absence of liquid phase aeration. Effluent COD values with liquid phase aeration were significantly lower than those obtained without liquid phase aeration indicating significant advantage of liquid phase aeration at high COD loading rates. The difference between the two cases is negligible at low COD loading rates of $L_s < 3000$ mg COD/ m^2.h.

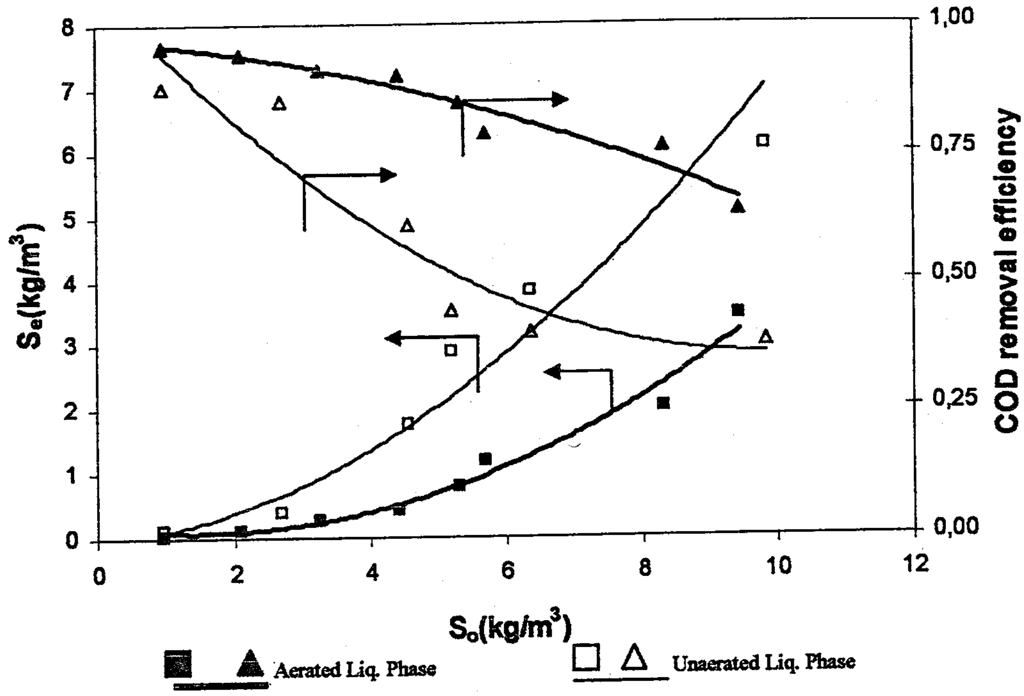

Figure 3.2.2 Variation of effluent COD and COD removal efficiency with the feed COD

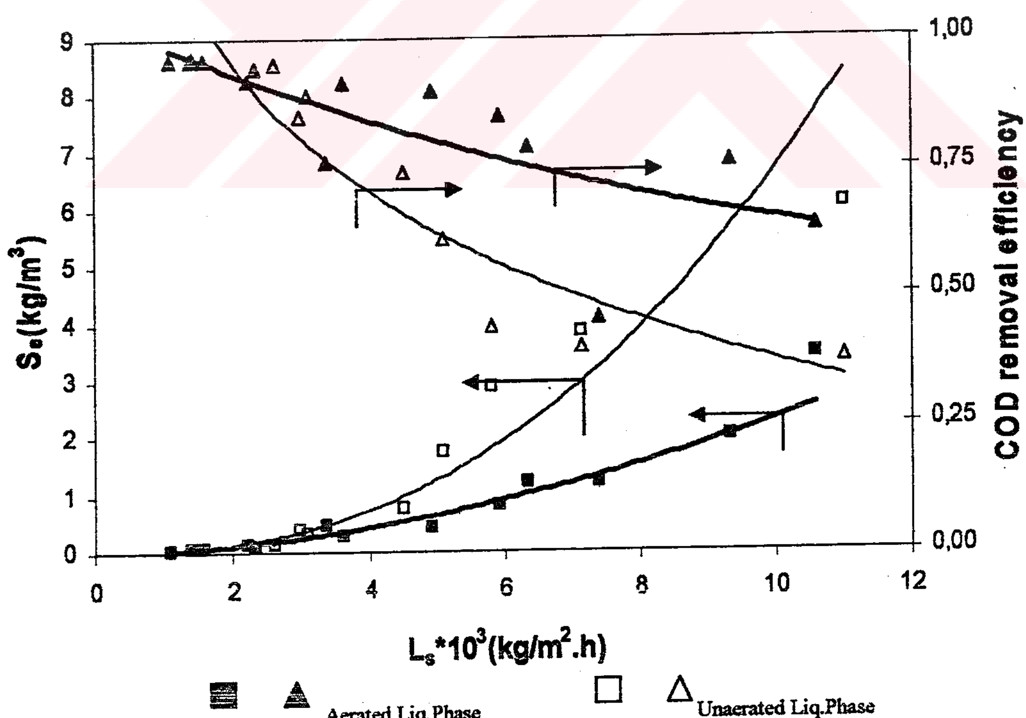

Figure 3.2.3 Variation of effluent COD and COD removal efficiency with COD loading rate

Figure 3.2.4 depicts variation of COD removal rate (R_s) with COD loading rate (L_s = Q S_o/A) in the presence and absence of liquid phase aeration. The rate increased with increasing COD loading rate for both cases. The rate of COD removal with aerated liquid phase was significantly higher than that of the unaerated liquid phase, especially at high COD loading rates. The difference between the two cases at low COD loading rates ($L_s < 3.\ 10^{-3}$ kg COD/ m^2.h) was negligible.

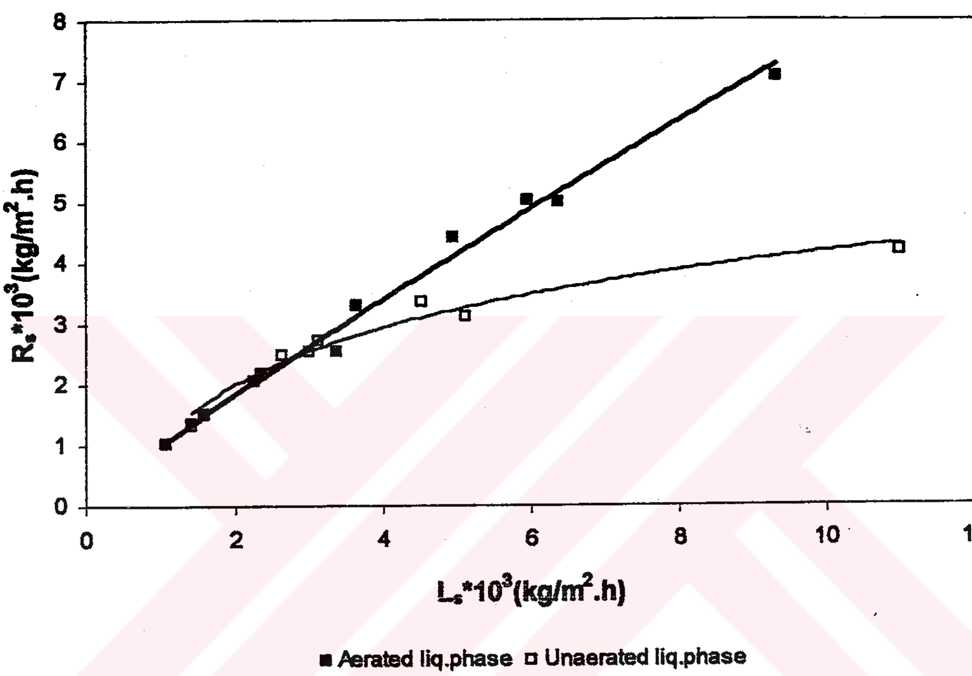

Figure 3.2.4 Variation of COD removal rate (R_s) with COD loading rate (L_s)

3.2.3. Kinetic Analysis of the System

Since liquid phase aeration was proven to be advantageous for treatment of high strength wastewaters, the kinetic analysis presented in this section covers the case of aerated liquid phase. By assuming Monod type COD removal kinetics, a COD balance around the reactor yields the following equation:

$$Q\,(S_o - S) = \frac{k_f X_f S}{K_s + S} A + \frac{k_s X_s S}{K_s + S} V = \frac{R_{mf} S}{K_s + S} A + \frac{R_{ms} S}{K_s + S} V \qquad (3.8)$$

The first term on the right hand side of eqn 3.8 represents COD removal rate by the biofilm organisms and the second term by the suspended organisms in liquid phase.

Equation 3.8 can be rearranged as,

$$Q\,(So - S) = (R_{mf} + R_{ms} / a)\,\frac{S}{K_s + S}\,A = \frac{R_m\,S}{K_s + S}\,A \qquad (3.9)$$

or

$$\frac{Q\,(S_o - S)}{A} = R_s = (R_{mf} + R_{ms} / a)\,\frac{S}{K_s + S} = \frac{R_m\,S}{K_s + S} \qquad (3.9a)$$

where, Q is flow rate of the feed wastewater (m^3/h); S_o and S are the feed and effluent COD (kg/m^3); A is the total biofilm surface area (m^2); k_f and k_s are maximum COD removal rate constants for biofilm and suspended organisms (d^{-1}); X_f and X_s are the biomass concentrations on the tube surfaces (kg /m^2) and in the liquid phase (kg/ m^3), respectively; K_s is the saturation constant (kg/ m^3), 'a' is the biofilm surface area per unit wastewater volume in the tank (m^2 surf.area/ m^3 ww volume), R_{mf} (kg COD/ m^2.h) and R_{ms} (kg COD/ m^3.h) are maximum COD removal rates for biofilm and suspended organisms, respectively. Since liquid phase was aerated, both biofilm and suspended cell's contributions for COD removal were considered in the analysis.

In double reciprocal form, eqn 3.9a may be written as,

$$\frac{1}{R} = \frac{A}{Q\,(S_o - S)} = \frac{1}{R_m} + \frac{K_s}{R_m}\,\frac{1}{S} \qquad (3.10)$$

A plot of 1/R versus 1/S yields a line, with a slope of K_s/R_m and an intercept of $1/R_m$.

Experimental data obtained with different flow rates at constant feed $COD_o \cong 2{,}000$ mg/L were plotted in form of A / Q (S_o- S) versus 1/S and from the slope and intercept of the best-fit line the following values were found for R_m and K_s (Figure 3.2.5).

$R_m = 3.4 \times 10^{-3}$ kg/ m^2.h =3400 mg/m^2.h and K_s = 110 mg/L = 0.11 kg/ m^3

Therefore, the rate eqn. may be written as,

$$R = \frac{R_m\ S}{K_s + S} = \frac{3{,}400\ S}{110 + S} \quad \text{where S is in mg/L and R is in mg/ } m^2\text{.h} \qquad (3.11)$$

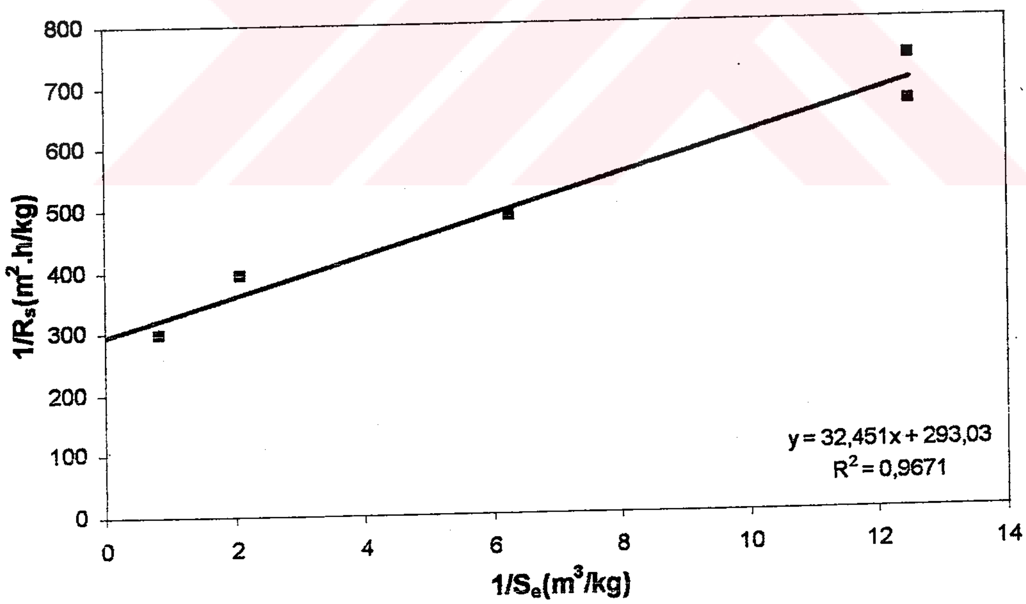

Figure 3.2.5 Double reciprocal plot of 1/Rs versus 1/S for determination of the kinetic constants.

3.2.4. Empirical Model Development

An empirical model describing the COD removal efficiency as a function of A/Q ratio and feed COD concentration was developed. The model has the following form:

$$E = 1 - \frac{S}{S_o} = a\,(A/Q)^b .\, S_o^c \qquad (3.12)$$

In linearized form this eqn.may be written as

$$\ln E = \ln a + b \ln (A/Q) + c \ln S_o \qquad (3.13)$$

Experimental data obtained at different flow rates or A/ Q ratio and constant feed COD of approximately, 2,000 mg/L were plotted in form of Ln E versus Ln (A/ Q). From the slope of the best-fit line the exponent 'b' was found as b = 0.48 ($R^2 = 0.91$).

Similarly, experimental data obtained at different feed COD (1,000- 11,000 mg/L) and constant A/Q of 894 $m^2.h/m^3$ were plotted in form of Ln E versus Ln S_o. From the slope of the best-fit line the exponent 'c' was found as c = - 0.16 ($R^2 = 0.92$). Also, from the intercept of the aforementioned plots the coefficient 'a' was found as a = 0.04.

Therefore, the empirical eqn has the following form,

$$E = 0.04\,(A/Q)^{0.48}\, S_o^{-0.16} \qquad (3.14)$$

COD removal efficiency of the system can be estimated by using eqn 3.14 for different operating conditions with liquid phase aeration.

Alternatively, COD removal efficiency was also correlated with COD loading rate by the following equation,

$$E = 1 - \frac{S}{S_o} = a_1 (Q\, S_o / A)^{b1} = a_1\, L_s^{b1} \tag{3.15}$$

In linearized form eqn 3.15 can be written as

$$\text{Ln } E = \text{Ln } a_1 + b_1 \text{ Ln } (L_s) \tag{3.16}$$

Experimental data was plotted in form of Ln E versus Ln (L_s) and from the slope and intercept of the best-fit line the constants were found as $a_1 = 0.46$ and $b_1 = -0.11$ ($r^2 = 0.89$).

Therefore, eqn 3.15 takes the following form.

$$E = 0.46\, (L_s)^{-0.11} \tag{3.17}$$

3.3 Comparison of RPT and RBD under the same conditions.

Two sets of experiments were conducted with each system. In the first set of experiments, the feed COD concentration was kept approximately constant at $COD_o = 2000 \pm 200$ mg/L and the A/Q ratio was changed by varying the feed flow rate. In the second set of experiments the feed flow rate was kept constant to yield A/Q = 894 $m^2.h/m^3$ and the feed COD was changed between 1,000 and 10,000 mg/L in order to change the COD loading rate.

3.3.1 Experiments with Different Feed Flow Rates

Feed flow rate was changed in this set of experiments while the feed COD was kept constant at $COD_o = 2000 \pm 200$ mg/L. The results of this set of experiments are depicted in Figure 3.3.1 in form of effluent COD and COD removal efficiency versus A/Q ratio. Effluent COD decreased and COD removal efficiency increased with increasing A/Q ratio for both RBD and RPT biofilm reactors. However, the decrease in effluent COD or increase in COD removal efficiency (E) were more significant in rotating perforated tubes (RPT) as compared to rotating bio-discs (RBD). COD removal efficiency (E) increased from 68% at A/Q = 298 $m^2.h/m^3$ to 96% at A/Q = 1489 $m^2.h/m^3$ with RPT. However, increases in COD removal efficiency with the RBD were from 32% to 79% for the same values of A/Q ratio.

The differences between COD removal performances of both reactors become more significant in favor of RPT at low A/Q ratios. These results clearly indicated the fact that RPT was more advantageous as compared to the RBD reactor.

Figure 3.3.2 depicts variation of COD removal rate (R_s = Q.(So-S)/A) with A/Q ratio for both reactors. Since Q was decreased in order to increase A/Q ratio, R_s values decreased although the effluent COD (S) gets smaller and (So-S) gets larger at high A/Q ratios. This drop was sharper with RPT as compared to RBD as shown in Figure 3.3.2. At low A/Q ratios, the rate of COD removal (R_s) with RPT was significantly larger than the R_s values obtained with RBD. However, at high A/Q ratios such as A/Q > 1200 $m^2.h/m^3$ this difference becomes negligible. Since the operation at low A/Q ratios is preferable, RPT is clearly more advantageous as compared RBD.

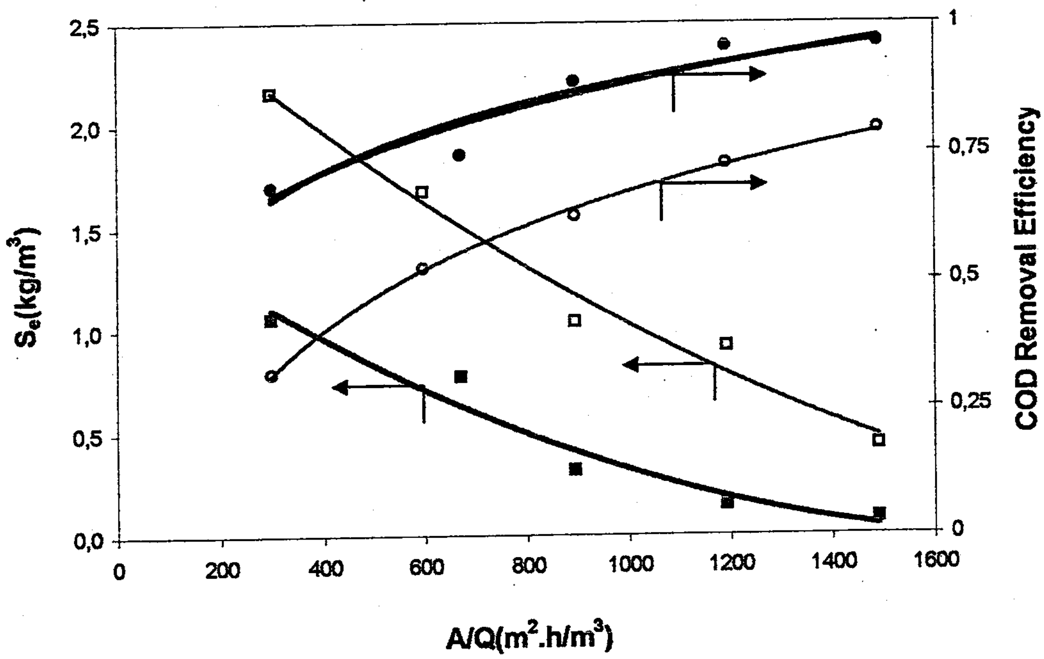

Figure 3.3.1. Comparison of effluent COD and COD removal efficiency as a function of A/Q ratio for RPT and RBD

■ ● RPT　　□ ○ RBD

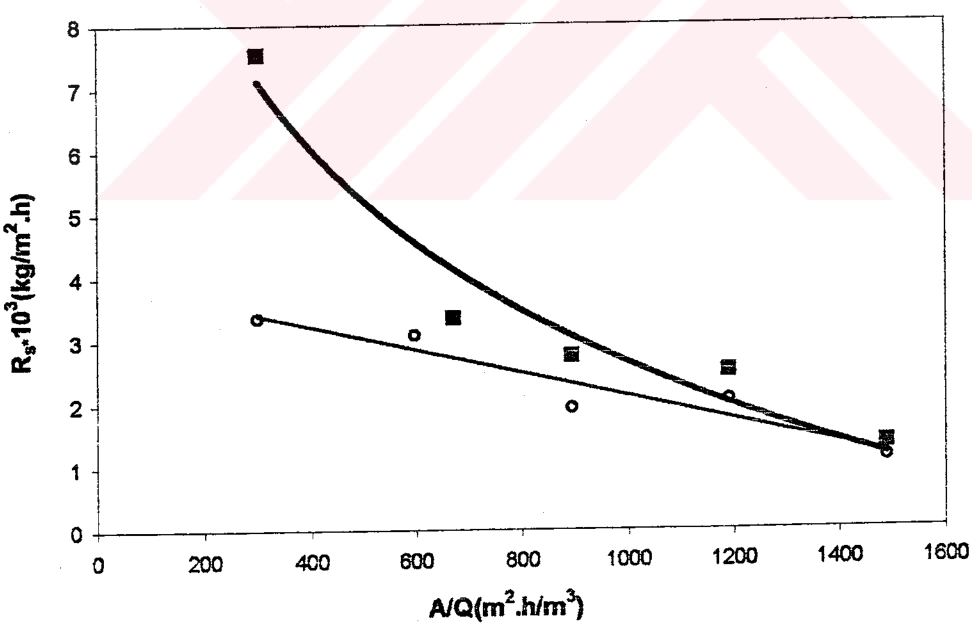

Figure 3.3.2. Variation of COD removal rate with A/Q ratio for RPT and RBD

■ RPT　　○ RBD

3.3.2 Experiments with Different Feed COD concentrations

Major objective in this set of experiments was to investigate variations of COD removal efficiencies with the feed COD and COD loading rate for both systems. Feed wastewater flow rate was kept constant to yield $\theta_H = 6$ h or A/Q = 894 $m^2.h/m^3$ while the feed COD varied between 1,000 mg/L and 10,000 mg/L.

Figure 3.3.3 depicts variation of the effluent COD and COD removal efficiency with the feed COD for both RPT and RBD. As seen from the figure, the effluent COD increased and COD removal efficiency (E) decreased with increasing feed COD. However, the extent of drop in efficiency was more significant with the RBD as compared to the RPT. At low feed COD concentrations the performances of both systems were comparable; however, at high feed COD values RPT results in lower effluent COD values or higher COD removal efficiencies as compared to the RBD. These results indicate clear advantage of RPT over RBD for high strength wastewater treatment.

Variations of the feed COD and COD removal efficiency with the COD loading rate ($L_s = Q\ S_o/A$) are depicted in Figure 3.3.4. Effluent COD increased with increasing COD loading rate for both systems, as expected. However, effluent COD values obtained with RBD were higher than those of RPT indicating clear advantage of RPT over RBD. A similar trend was observed when COD removal efficiencies were compared for both systems. COD removal efficiencies obtained with the RPT were larger than those obtained with the RBD at all COD loading rates tested. This difference is more significant at high COD loading rates.

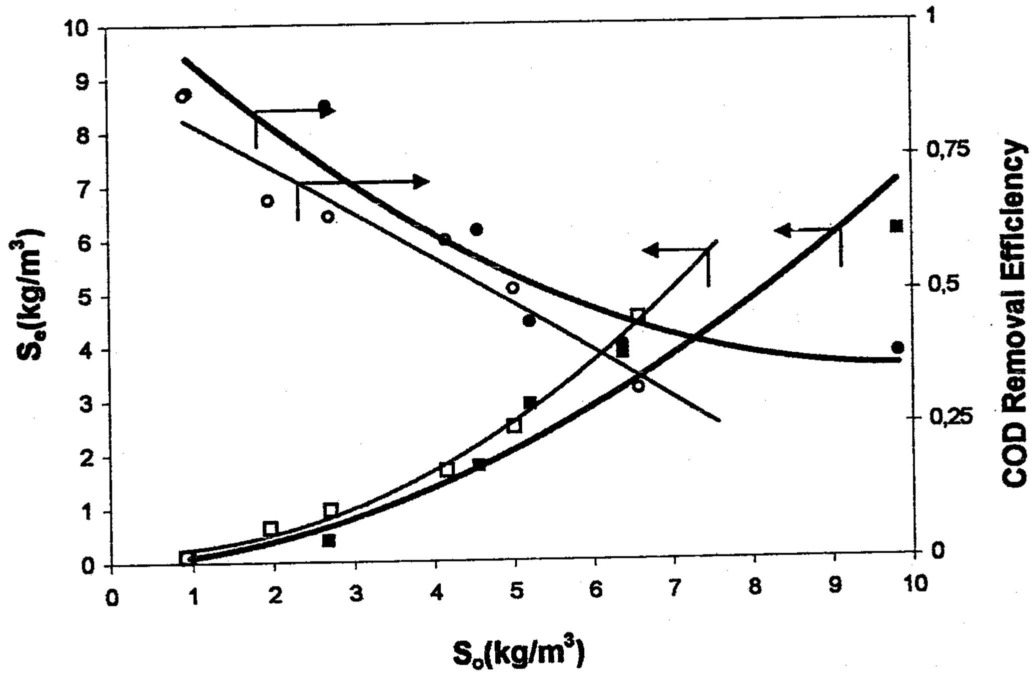

Figure 3.3.3. Variation of effluent COD and COD removal efficiency with the feed COD for RPT and RBD

■ ● RPT □ ○ RBD

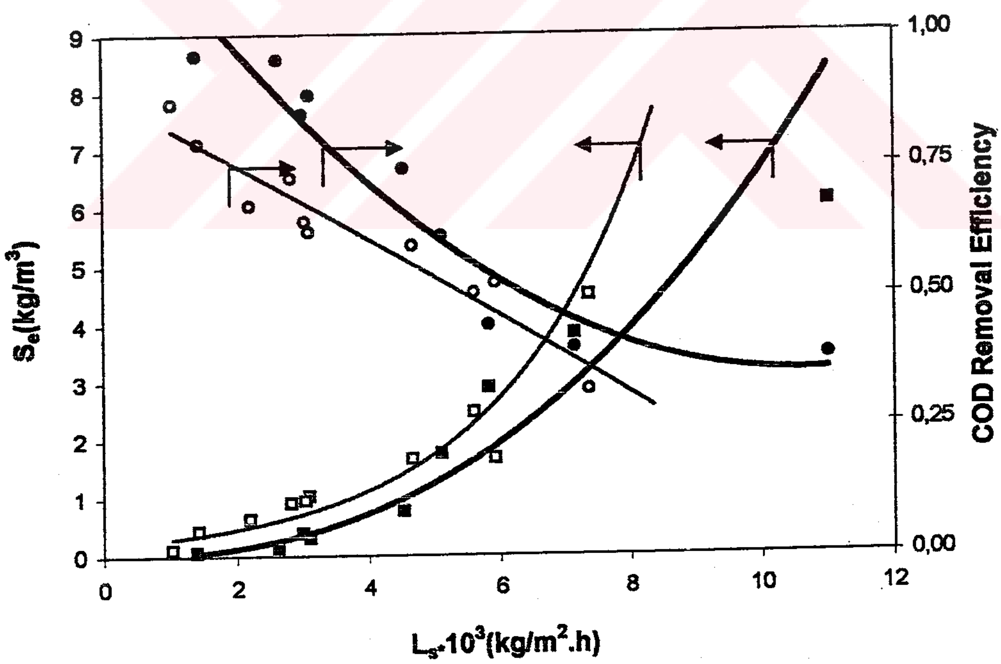

Figure 3.3.4. Variation of effluent COD and COD removal efficiency with COD loading rate for RPT and RBD

■ ● RPT □ ○ RBD

3.3.3 Empirical Model Development for RBD and Comparison of Empirical Design equations for RPT and RBD

Empirical models were developed to estimate the systems' performance as functions of important process variables such as A/Q ratio and the feed COD (S_o).

The proposed equation has the following form:

$$E = 1 - \frac{S}{So} = a\,(A/Q)^b\,(So)^c \qquad (3.18)$$

In linearized form the eqn 3.18 can be written as follows,

$$LnE = Ln\,a + b\,Ln\,(A/Q) + c\,LnSo \qquad (3.19)$$

Experimental data obtained at constant S_o of 2000 ± 200 mg/L and variable feed flow rate were plotted in form of Ln E versus Ln (A/Q) for both systems. From the slope of the best-fit lines the exponent (b) was found to be b = 0.24 for the RPT ($r^2 = 0.90$) and b= 0.57 for the RBD ($r^2 = 0.99$).

Similarly, experimental data collected at constant A/Q value of 894 $m^2.h/m^3$ and variable S_o of between 1000 and 10,000 mg/L were plotted in form of Ln E versus Ln S_o for both systems. From the slope of the best fit-lines the exponent (c) was found to be c= - 0.2 for the RPT ($r^2 = 0.93$) and c = -0.29 for the RBD ($r^2 = 0.95$). From the intercepts of both lines with the y-axis the constant (a) was found to be a= 0.21 for the RPT and a = 0.02 for RBD.

As an alternative approach, the COD removal efficiency (E) can be correlated with the COD loading rate ($L_s = Q\,S_o/A$) as follows:

$$E = 1 - \frac{S}{S_o} = a\,L_s^{\,b} \qquad (3.20)$$

In linearized form eqn 3.20 can be written as,

$$\text{Ln } E = \text{Ln } a + b \text{ Ln } (L_s) \tag{3.21}$$

Experimental data were plotted in form of Ln E versus Ln L_s and from the slope of the best-fit line the constants were found to be a = 0.37 and b= -0.14 for the RPT (r^2 = 0.86). The constants for the RBD were found as a = 0.12 and b= - 0.29 (r^2 = 0.92) by using a similar procedure.

The final forms of the empirical equations with the experimentally determined constants are summarized in Table 3.3.1 for both biofilm reactors.

Table 3.3.3.1. Comparison of empirical design equations for RPT and RBD.

Reactor type	**Design Equations**
RPT	$E = 0.21\,(A/Q)^{0.24}\,(S_o)^{-0.2}$ or $E = 0.37\,(L_s)^{-0.14}$
RBD	$E = 0.02\,(A/Q)^{0.57}\,(S_o)^{-0.29}$ or $E = 0.12\,(L_s)^{-0.29}$

As can be seen from the Table 3.3.3.1, RPT is more advantageous as compared to the RBD resulting in higher COD removal efficiencies under the same conditions.

CHAPTER FOUR

CONCLUSIONS

A novel biofilm reactor named as 'rotating perforated tubes biofilm reactor' (RPT) was developed and used for synthetic wastewater treatment with and without liquid phase aeration. Performances of RPT were compared with rotating biodisc reactors (RBD) under the same conditions as a function of major process variables.

Effects of major process variables such as A/Q ratio, feed COD concentration and COD loading rate on the rate and extent of COD removal were determined for both reactors. Empirical design equations were developed to describe reactors' behavior and the constants were determined by using the experimental data.

When RPT was operated without liquid phase aeration, the effluent COD decreased and COD removal efficiency increased with increasing A/Q ratio. In order to obtain COD removal efficiency larger than $E > 0.95$, the A/Q ratio should be larger than $A/Q > 1{,}200\ m^2.h/\ m^3$.

The effluent COD increased and COD removal efficiency decreased with increasing feed COD. This variation is more significant especially for feed COD of above 3,000 mg/L (3 kg/ m^3) m^3 without liquid phase aeration in RPT.

Increasing COD loading rate resulted in significant decreases in COD removal efficiency especially for L_s values above 3,000 mg/ m^2.h. COD loading rate should be kept below $L_s < 3000$ mg/ m^2.h for more than 90% COD removal by the RPT reactor without liquid phase aeration.

When the rotational speed of the tubes varied between 3 rpm and 12 rpm, the effluent COD decreased and COD removal efficiency increased with increasing rotational speed. The maximum percent COD removal obtained at 12 rpm was 92%.

COD removal efficiency decreased with decreasing number of the perforated tubes from 90% with 50 tubes to 76% with 44 tubes and to 39% with 14 tubes when the flow rate and COD content of the feed wastewater were constant.

When the liquid phase was aerated, the effluent COD increased and COD removal efficiency decreased with increasing feed COD. This variation was more significant especially for feed COD values above 3,000 mg/L (3 kg/ m^3). Liquid phase aeration was proven to be significantly advantageous especially for high strength wastewaters of COD_o >3,000 mg/ L resulting in lower effluent COD levels or higher COD removal efficiencies as compared to the results of un-aerated liquid phase

When the performances of RPT and RBD were compared under the same experimental conditions, COD removal efficiency increased with increasing A/Q ratio; however, decreased with increasing feed COD concentration and COD loading rate for both reactors. In general, COD removal efficiencies obtained with RPT were higher than those obtained with the RBD. The RPT was found to be more advantageous especially at low A/Q ratio and high COD loading rates as compared to RBD.

Empirical design equations were developed for both RPT and RBD and the constants were determined by using the experimental data. Based on the constants of the empirical design equations, it is obvious that the RPT results in better COD removal efficiencies as compared to the RBD. Therefore, the RPT can be preferably used over RBD for wastewater treatment.

RECOMMENDATIONS

Following recommendations can be made for future studies on rotating perforated tubes biofilm (RPT) reactor:

1. Design of the reactor can be improved to obtain better results

2. The reactor can be used for treatment of some industrial wastewaters of interest such as food and chemical industries

3. Biological oxidation of toxic chemicals can be studied in this reactor under different conditions. Toxicity removal can be quantified.

4. The RPT reactor can be used for nitrification and denitrification.

5. The reactor can be used for nutrient removal (N, P) from wastewaters

6. The system can be operated at larger ranges of the operating parameters such as the rotational speed, A/Q ratio and COD loading rates to determine the performance.

NOMENCLATURE

A	surface area of the perforated tubes or discs (m^2)
A_w	wet surface area of the perforated tubes or discs (m^2)
a	surface area of discs per unit volume of liquid (m^2/m^3)
COD	chemical oxygen demand (kg/m^3)
E	efficiency of COD removal
K_s	saturation constant (kg/m^3)
k_f	rate constant for COD removal by biofilm (h^{-1})
k_s	rate constant for COD removal by suspended cells (h^{-1})
k	maximum substrate utilization coefficient (d^{-1})
L_s	surface COD loading rate (kgCOD/m^2.h)
N	number of perforated tubes
Q	flow rate of wastewater (m^3/h)
R_{mf}	maximum surface COD removal rate by biofilm (kgCOD/m^2.h)
R_{ms}	maximum COD removal rate by suspended cells (kg COD/m^3.h)
R_{mT}	total maximum COD removal rate (kg COD/ m^2.h)
R_s	COD removal rate based on surface area of perforated tubes or discs (kgCOD/ m^2.h)
R_x	specific rate of COD removal (kg COD/ kg.biomass.h)
S, S_e	COD in effluent wastewater (kg/m^3)
S_o	COD in feed wastewater (kg/m^3)
V	volume of reactor (m^3)
X_f	biomass concentration in form of biofilm (kgdw/m^2)
X_s	biomass concentration suspended in liquid (kg dw/m^3)
Y	growth yield coefficient (kgX/kgS)
μ_{mf}	maximum specific rate of growth for biofilm organisms (h^{-1})
μ_{ms}	maximum specific rate of growth for suspended cells (h^{-1})
θ_H	hydraulic residence time (h)

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5.2. APPENDICIES

5.2.1. Raw Data for Rotating Perforated tubes Biofilm Reactor

Table 5.1. Effect of A/Q ratio system's performance for RPT without liquid phase aeration

Q_H(h)	So(kg/m^3)	Se(kg/m^3)	Q(L/h)	Ls($kg/m^2.h$)	Ls($kg/10^3.m^2.h$)	Rs($kg/m^2.h$)	Rs($kg/10^3 m^2.h$)	E	A/Q($m^2.h/m^3$)	1/Se(m^3/kg)	A/Q(Si-Se) ($m^2.h/kg$)
2	3,303	1,060	4,5	0,01109	11,09	0,00753	7,53	0,68	298	0,943	132,788
4	3,025	0,778	2	0,00451	4,51	0,00335	3,35	0,74	670	1,286	298,109
6	2,765	0,318	1,5	0,00310	3,10	0,00274	2,74	0,89	893	3,150	364,998
8	3,125	0,145	1,125	0,00262	2,62	0,00250	2,50	0,95	1191	6,897	399,702
10	2,080	0,080	0,9	0,00140	1,40	0,00134	1,34	0,96	1489	12,500	744,444

Table 5.2. Effect of feed COD concentration on system's performance for RPT without liquid phase aeration

Q_H(h)	So(kg/m^3)	Se(kg/m^3)	Q(L/h)	Ls($kg/m^2.h$)	Ls($kg/10^3.m^2.h$)	Rs($kg/m^2.h$)	Rs($kg/10^3 m^2.h$)	E(%)	A/Q($m^2.h/m^3$)	1/Se(m^3/kg)	A/Q(Si-Se) ($m^2.h/kg$)
6	0,960	0,120	1,5	0,00107	1,07	0,00094	0,94	0,88	893	8,333	1063,492
6	1,485	0,283	1,5	0,00166	1,66	0,00135	1,35	0,81	893	3,534	743,206
6	2,673	0,405	1,5	0,00299	2,99	0,00254	2,54	0,85	893	2,469	393,886
6	3,440	0,680	1,5	0,00385	3,85	0,00309	3,09	0,80	893	1,471	323,671
6	4,560	1,760	1,5	0,00510	5,10	0,00313	3,13	0,61	893	0,568	319,048
6	5,200	2,900	1,5	0,00582	5,82	0,00257	2,57	0,44	893	0,345	388,406
6	6,360	3,830	1,5	0,00712	7,12	0,00283	2,83	0,40	893	0,261	353,096
6	9,820	6,080	1,5	0,01099	10,99	0,00419	4,19	0,38	893	0,164	238,859

Table 5.3. Effect of A/Q ratio system's performance for RPT with liquid phase aeration

Q_H(h)	So(kg/m³)	Se(kg/m³)	Q(m³/10³h)	Ls(kg/m².h)	Ls(kg/10³.m².h)	Rs(kg/m².h)	Rs(kg/10³.m².h)	E	A/Q(m².h/m³)	1/Se(m³/kg)	A/Q(Si-Se) (m².h/kg)
2	2,20	1,20	4,50	0,007388	7,39	0,003358	3,36	0,45	298	0,8	297,78
4	2,00	0,48	2,25	0,003358	3,36	0,002552	2,55	0,76	596	2,1	391,81
6	2,00	0,16	1,50	0,002239	2,24	0,002060	2,06	0,92	893	6,3	485,51
8	1,88	0,08	1,13	0,001578	1,58	0,001511	1,51	0,96	1191	12,5	661,73
10	2,10	0,08	0,90	0,001410	1,41	0,001357	1,36	0,96	1489	12,5	737,07

Table 5.4. Effect of feed COD concentration on system's performance for RPT with liquid phase aeration

Q_H(h)	So(kg/m³)	Se(kg/m³)	Q(m³/10³h)	Ls(kg/m².h)	Ls(kg/10³.m².h)	Rs(kg/m².h)	Rs(kg/10³.m².h)	E	A/Q(m².h/m³)	1/Se(m³/kg)	A/Q(Si-Se) (m².h/kg)
6	0,96	0,04	1,50	0,001075	1,07	0,001030	1,03	0,96	893	25,0	971,01
6	2,08	0,12	1,50	0,002328	2,33	0,002194	2,19	0,94	893	8,3	455,78
6	3,24	0,28	1,50	0,003627	3,63	0,003313	3,31	0,91	893	3,6	301,80
6	4,40	0,44	1,50	0,004925	4,93	0,004433	4,43	0,90	893	2,3	225,59
6	5,30	0,80	1,50	0,005933	5,93	0,005037	5,04	0,85	893	1,3	198,52
6	5,68	1,20	1,50	0,006358	6,36	0,005015	5,01	0,79	893	0,8	199,40
6	8,32	2,00	1,50	0,009313	9,31	0,007075	7,07	0,76	893	0,5	141,35
6	9,44	3,44	1,50	0,010567	10,57	0,006716	6,72	0,64	893	0,3	148,89

Table 5.5. Rotational speed of perforated tubes

Q_H(h)	rpm	So(kg/m^3)	Se(kg/m^3)	Q(L/h)	Ls(kg/m^2.h)	Ls(kg/10^3.m^2.h)	Rs(kg/m^2.h)	Rs(kg/10^{3}m^2.h)	E	A/Q(m^2.h/m^3)	1/Se(m^3/kg)	A/Q(Si-Se) (m^2.h/kg)
6	3	1,871	0,538	1,5	0,00209	2,09	0,00149	1,49	0,71	893	1,859	670,168
6	5	2,235	0,812	1,5	0,00250	2,50	0,00159	1,59	0,64	893	1,232	627,782
6	7	2,100	0,500	1,5	0,00235	2,35	0,00179	1,79	0,76	893	2,000	558,333
6	9	1,875	0,114	1,5	0,00210	2,10	0,00197	1,97	0,94	893	8,772	507,288
6	12	2,130	0,150	1,5	0,00238	2,38	0,00222	2,22	0,93	893	6,667	451,178

Table 5.6. Number of perforated tubes

N.of Tubes	A(m^2)	Q_H(h)	So(kg/m^3)	Se(kg/m3)	Q(L/h)	Ls(kg/10^{3}m^2.h)	Rs(kg/10^{3}m2.h)	E	A/Q(m2.h/m3)
50	1,34	6	2,673	0,405	1,5	2,990	2,540	0,85	893
44	1,18	6	2,113	0,5	1,5	2,686	2,050	0,76	787
32	0,86	6	2,2	0,718	1,5	3,837	2,585	0,67	573
26	0,7	6	2,145	0,72	1,5	4,596	2,946	0,64	467
20	0,54	6	1,96	0,9	1,5	5,444	2,944	0,54	357
14	0,38	6	2,11	1,29	1,5	8,329	3,237	0,39	253

5.2.2. Raw Data for Rotating Biodisc Reactor

Table 5.7. Effect of A/Q ratio system's performance for RBD without liquid phase aeration

Q_H(h)	So(kg/m^3)	Se(kg/m^3)	Q(m^3/h)	Ls(kg/m^2.h)	Ls(kg/10^3.m^2.h)	Rs(kg/m^2.h)	Rs(kg/10^3.m^2.h)	E	A/Q(m^2.h/m^3)	1/Se(m^3/kg)	A/Q(Si-Se) (m^2.h/kg)
2	3,16	2,16	4,50	0,010612	10,61	0,003358	3,36	0,32	298	0,5	297,78
4	3,52	1,68	2,25	0,005910	5,91	0,003090	3,09	0,52	596	0,6	323,67
6	2,76	1,04	1,50	0,003090	3,09	0,001925	1,93	0,62	893	1,0	519,38
8	3,36	0,92	1,13	0,002821	2,82	0,002049	2,05	0,73	1191	1,1	488,16
10	2,12	0,44	0,90	0,001424	1,42	0,001128	1,13	0,79	1489	2,3	886,24

Table 5.8. Effect of feed COD concentration on system's performance for RBD without liquid phase aeration

Q_H(h)	So(kg/m^3)	Se(kg/m^3)	Q(m^3/h)	Ls(kg/m^2.h)	Ls(kg/10^3.m^2.h)	Rs(kg/m^2.h)	Rs(kg/10^3.m^2.h)	E	A/Q(m^2.h/m^3)	1/Se(m^3/kg)	A/Q(Si-Se) (m^2.h/kg)
6	0,92	0,12	1,50	0,001030	1,03	0,000896	0,90	0,87	893	8,3	1116,67
6	1,96	0,64	1,50	0,002194	2,19	0,001478	1,48	0,67	893	1,6	676,77
6	2,71	0,97	1,50	0,003034	3,03	0,001948	1,95	0,64	893	1,0	513,41
6	4,16	1,68	1,50	0,004657	4,66	0,002776	2,78	0,60	893	0,6	360,22
6	5,00	2,48	1,50	0,005597	5,60	0,002821	2,82	0,50	893	0,4	354,50
6	6,56	4,48	1,50	0,007343	7,34	0,002328	2,33	0,32	893	0,2	429,49