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Hydrodynamic Characteristics in Aerobic Biofilm Reactor Treating High-Strength Trade Effluent

H. CHUA*,[1] AND P. H. F. YU[2]

Departments of [1]Civil and Structural Engineering; and [2]Applied Biology and Chemical Technology, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

ABSTRACT

Four 3-L aerobic biofilm reactors (ABR1, 2, 3, and 4) treating a high-strength food-processing waste water (10 g chemical oxygen demand [COD]/L) were subject to reactor liquor recirculation rates of 1, 3, 15, and 30 L/h, respectively. Treatment performance in terms of COD removal rates of ABR1, 2, and 3 were similar at hydraulic loads of 2.0 g COD/L/d and below. At higher organic loads, ABR3 could achieve a COD removal rate that was over two times higher than that of ABR1 and 2. ABR3 could be operated at a maximum organic load that was two times higher than that of ABR1 and 2. ABR4 experienced a biofilm sloughing from the packing medium at the beginning of operation. Tracer studies showed that recirculation rate of 1 L/h resulted in a plug-flow pattern in the packed bed of the reactor. On the other hand, recirculation rate of 15 L/h, which was equivalent to recirculating the reactor liquor five times per hour, provided effective mixing in the packed bed. Superior performance of ABR3 was attributed to the effective recirculation of reactor liquor, which diluted and distributed the influent, particularly the oil and grease components.

Index Entries: Aerobic biofilm reactor; recirculation rate; high-strength waste water; treatment performance; mixing.

INTRODUCTION

Immobilized biofilm technology has become popular for high-rate aerobic and anaerobic treatments of waste waters with low suspended solids and high organic strengths *(1–4)*. Adequate mixing is essential in

*Author to whom all correspondence and reprint requests should be addressed.

high-rate treatment processes to ensure uniform distribution of substrate, sufficient biomass-substrate contact, and prevention of process instability owing to localized accumulations of toxic matters *(5)*. Adequate mixing is also important to improve oxygen transfer and distribution in aerobic biofilm reactors. In the treatment of food-processing waste water, which contains a high concentration of oil and grease (500–1500 mg/L), adequate mixing is crucial in preventing oil droplets from adhering on and coating the biofilms.

Mixing in the packed bed of a biofilm reactor is only possible through effluent recirculation and aeration. DeWalle and Chian *(6)* reported that effluent recirculation could dilute the influent and maintain the COD removal efficiency with respect to the diluted influent. On the other hand, Thiramurthi *(7)* observed that an effluent recirculation beyond a threshold limit could cause process failure. However, very limited information is available on the complex hydrodynamics in the packed bed of a biofilm reactor and the effects of mixing on the treatment performances. This article assesses the effects of mixing on COD removal rate and the process stability of aerobic biofilm reactors treating a high-strength food-processing waste water. Hydrodynamic characteristics in the packed bed of the reactor are also modeled and described.

METHODS

Reactor System

The aerobic biofilm reactor is comprised of a column with a length-to-diameter ratio of 15 (Fig. 1). Four similar columns were packed with fire-expanded clay spheres (FECS) of average diameter 1.5 cm (Fig. 2). The effective volume of each column was 3 L. The reactor liquor was drawn from the top of the four columns, namely ABR1, 2, 3, and 4, and recirculated at 1, 3, 15, and 30 L/h, respectively, through the bottom. Compressed air was supplied, via a distributor, at the bottom of the reactor column. Each reactor was seeded with activated sludge from municipal sewage treatment works and was fed with a food-processing waste water of 10 g chemical oxygen demand (COD)/L for an initial 30-d seeding and acclimatization period. The stabilized reactors were then operated for another 90 d at organic loads of 1.0, 2.0, 5.0, 10.0, and 20.0 g COD/L/d.

Analytical Methods

The COD in the treated effluent was determined by the open reflux method. The volatile suspended solids (VSS) was measured by the volatilization and weighing method. Oil and grease concentrations were measured by the partition-gravimetric method. All the parameters were determined in accordance with the standard methods *(8)*.

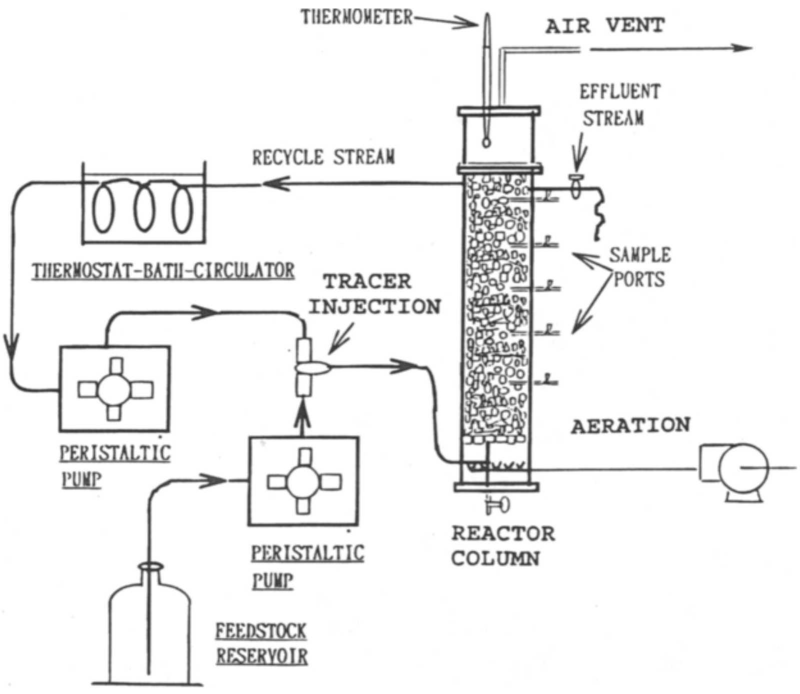

Fig. 1. Schematic diagram of aerobic biofilm reactor system.

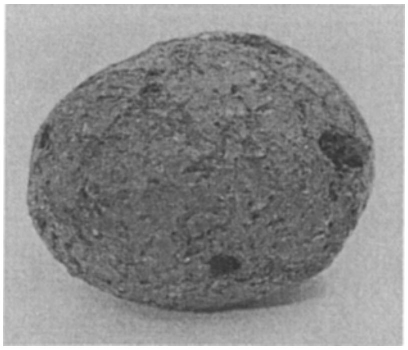

Fig. 2. Fire-expanded clay sphere used as packing medium.

Tracer Techniques

Tracer stimulus–response techniques described by Wakao and Kaguei *(9)* were used to study the residence time distribution (RTD) and flow patterns through the packed bed of the reactor. Experiments were carried out with ABR1 and 3, in which the reactor liquor was recirculated at a rate of 1 and 15 L/h, respectively. Both reactors were operated with an organic load of 10 g COD/L/d. Each tracer input was 30 mL of 500 mg/L sodium chlo-

Table 1
COD Removal Rates and Efficiencies

Organic Loads (gCOD/L-d)	COD Removal Rate (gCOD/L-d)				COD Removal Efficiency (%)			
	ABR1	ABR2	ABR3	ABR4	ABR1	ABR2	ABR3	ABR4
1.0	0.99	0.96	0.98	R.F.	98.8	96.0	97.9	R.F
2.0	1.97	1.94	1.96		98.7	96.9	97.9	
5.0	3.71*	3.99*	4.85		74.1	79.8	97.0	
10.0	R.F.**	R.F.	9.23*		R.F.	R.F.	92.3	
20.0			R.F.				R.F.	

*Optimum performance.
**Reactor failure.

ride solution, injected at the base of the reactor by a high-speed peristaltic dosing pump. Response to the tracer input was taken as a time record of chloride concentrations detected at the top of the reactor by a conductivity meter (LTH Electronics, Type PB5 with a Type CMC5/10/TIK electrode).

RESULTS AND DISCUSSION

Reactor Performances

The COD removal rates and removal efficiencies of the four aerobic biofilm reactors are summarized in Table 1. ABR1, 2, and 3 demonstrated similar performances in terms of COD removal rate and removal efficiency at organic loads of 1.0 and 2.0 g COD/Ld. As the organic load was increased to 5.0 g COD/L/d, the effects of recirculation began to show. COD removal rate and removal efficiency of ABR3 were significantly higher than that of ABR1 and 2. The COD removal rate of ABR3 reached an optimum of 9.23 g COD/L/d at organic load of 10.0 g COD/L/d, whereas that of ABR1 and 2 reached the optima of 3.71 and 3.99 g COD/L/d, respectively, at organic load of 5.0 g COD/L/d. ABR3 could be operated at an organic load that was two times higher than that of ABR1 and 2 before the reactors failed, while achieving a COD removal rate that was over two times higher than that of AR1 and 2. COD removal efficiency of ABR3 remained above 90% throughout the study before reactor failure, whereas that of ABR1 and 2 deteriorated when the organic load was increased to 5.0 g COD/L/d. Oil and grease removal efficiencies in ABR1 and 2 were between 54.6 and 63.2% under different loading rates. ABR3 could achieve an oil and grease removal efficiency as high as 79.7% under an organic loading rate of 10.0 g COD/L/d. Observations on ABR4 will be discussed later.

The optimum range of recirculation rates was around 15 L/h for achieving high COD, oil and grease removal rate, and removal efficiency at organic loads higher than 2.0 g COD/L/d. The recirculation rate of 15 L/h in ABR3 was equivalent to a superficial flow velocity of 480 cm/h. The effects of treated effluent recirculation on dilution and distribution of the organic load, and dispersion of the oil and grease enabled improved treatment performance in ABR3. However, at hydraulic loads of 2.0 g COD/L/d and below, operation with low recirculation rates was a more attractive option, because this could achieve COD removal rates and removal efficiencies that were comparable to that attained with high recirculation rates, while maintaining a lower cost of operation.

Biofilm

During the start-up stage, biomass was retained as suspended bioflocs in the interstices of the packed bed and loosely held biofilm on the surfaces of the packing medium. In ABR1, 2, and 3, the reactor liquor recirculation and the progressively increasing loading rates gradually displaced the excess suspended biomass, and established an uniform and firmly attached biofilm on the surfaces and in the pores of the packing medium (Fig. 3). The VSS concentration in the treated effluent gradually decreased from 617–890 mg/L during the initial 30-d period after seeding, to below 50 mg/L during the entire 90-d operating period of this study. On the other hand, the recirculation rate of 30 L/h in ABR4 resulted in a high superficial flow velocity, 960 cm/h, as experienced by the biofilm. This hydraulic shear caused a sloughing of biofilm from the packing medium at the beginning of operation, which resulted in reactor failure.

Hydrodynamic Characteristics

Tracer studies of the reactors ABR1 and 3 were carried out with recirculation rates of 1 and 15 L/h, respectively, and an organic load of 10.0 g COD/L/d. ABR1 represented reactors with inadequate mixing, and ABR3 represented reactors operated with adequate mixing and produced excellent COD removal rates. The recirculation rates of 1 and 15 L/h were equivalent to recirculating the filter liquor 1/3 and 5 times/h, respectively, and the loading rate was equivalent to a hydraulic retention time of 1 d. The RTDs as indicated by the tracer were plotted in terms of mg/L of chloride vs time in hours (Fig. 4).

The tracer input was approximated by a tall, narrow square wave, represented by the vertical arrow at zero time in Fig. 4. The response signal for ABR1 was a skewed peak that had a sharp, rapidly increasing positive slope and a slow decreasing tail. The lag time was about 23 h, which agreed very closely with the operating hydraulic retention time (HRT) of 1 d. This was a typical response configuration of a plug-flow system with moderate amounts of dispersion. The response signal for ABR3 resembled the typical profile of an ideal mixed-flow system, which could be represented mathematically by an exponential decay function. The response to the

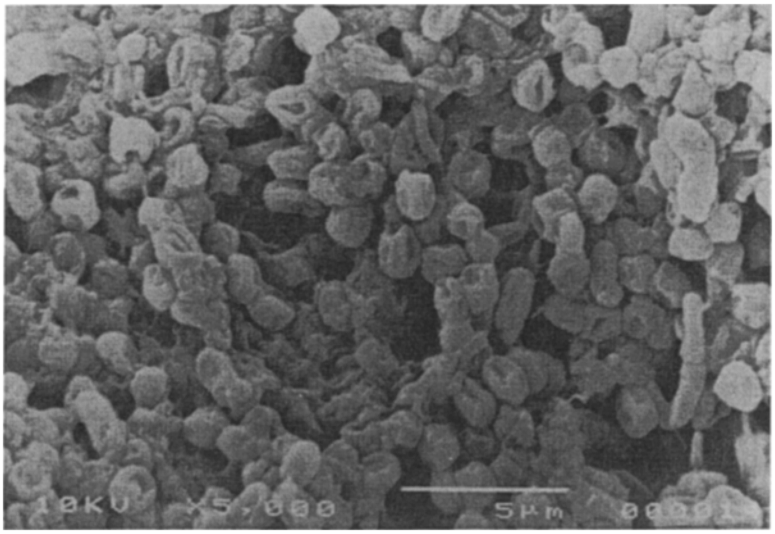

Fig. 3. Biofilm used as packing medium.

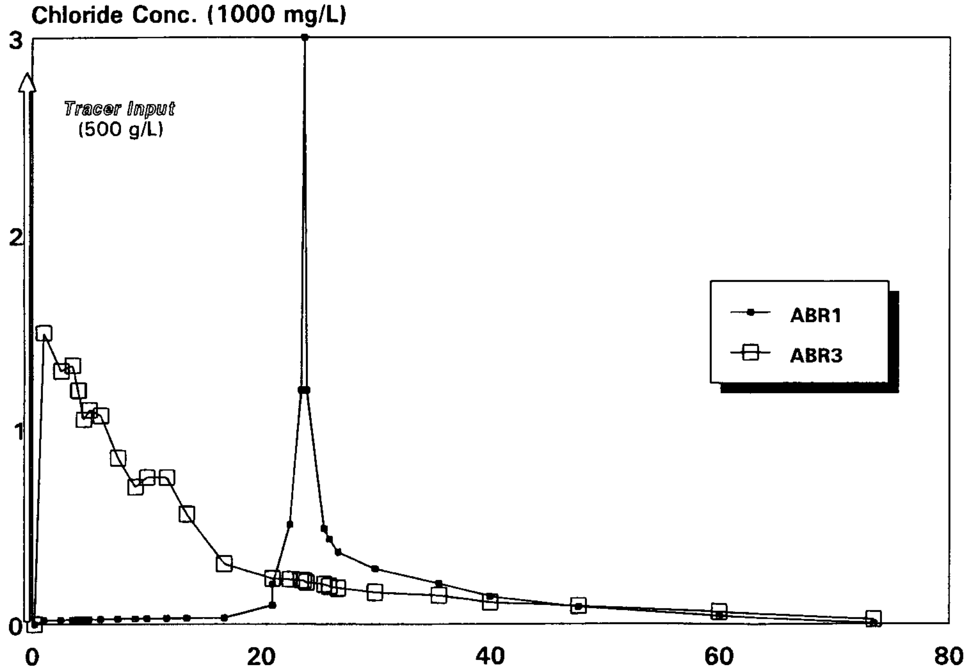

Fig. 4. Residence time distribution in aerobic biofilm reactor.

tracer input was almost instantaneous with a short lag time of about 10 min, which is not visible with the resolution of Fig. 4.

The mean residence time, variance, and dispersion number of the reactors was calculated by the dispersion model presented by Eqs. (1), (2), and (3). The flow pattern in the reactor was described by the single-parameter, dispersion model, which considered the flow in a packed bed to be in a plug-flow pattern with different degrees of dispersion in the axial direction. With varying intensity of dispersion, the predictions of the model ranged from ideal plug flow at one extreme to ideal mixed flow at the other. The model correlated the mean residence time and variance of the RTD curve, obtained through tracer methods, by Eq. (1).

$$S^2/t^2 = 2(D/UL) - 2(D/UL)^2\,[1 - \exp(UL/D)] \quad (1)$$

where S^2 = variance of the RTD curve, h^2; t = mean residence time of the RTD curve, h; D/UL = dispersion number, dimensionless; D = axial dispersion coefficient, m^2/h; U = interstitial fluid velocity, m/h; and L = length of reactor column, m. The dimensionless dispersion number (D/UL), the single parameter of the dispersion model, provided a measure of the extent of axial dispersion. The mean residence time (t) located the center of gravity of the RTD curve and was calculated by Eq. (2).

$$t = [SUM(t_iC_it_i')/SUM(C_it_i')] \quad (2)$$

where t_i = time after the tracer was introduced, h; C_i = concentration of sodium chloride in the sample taken from the reactor at time t_i, mg/L; and t_i = interval between successive samples, h; SUM denotes the summation of the argument in the parentheses through each tracer experiment. The variance described the spread of the RTD curve and was given by Eq. (3).

$$S^2 = [SUM(t_iC_it_i')/SUM(C_it_i')] - t^2 \quad (3)$$

Table 2 summarizes published values of dispersion numbers for various extents of mixing as predicted by the dispersion model *(10)*. The dispersion number of 0.06 (Table 3) obtained for ABR1 with recirculation rate of 1 L/h indicated that the reactor was essentially a plug-flow column with an intermediate amount of dispersion. This observed dispersion, resulting in the deviation from the truly plug-flow hydrodynamics, which was expected for the packed-bed column with inadequate mixing, was attributed to the slow recirculation, and the diffusion and eddies generated when fluid flowed through the interstitial channels of the packed bed. On the other hand, the dispersion number of 0.65 obtained for ABR3 with recirculation at a rate of 15 L/hr was in the regime where there was a large extent of dispersion (D/UL > 0.2). The recirculation rate of 60 L/h provided effective mixing in the packed bed of the reactor. It was possible that a recirculation rate lower than 60 L/h could also achieve adequate mixing. This could be optimized if necessary.

CONCLUSION

The optimum range of recirculation rates was around 15 L/h for achieving high COD removal rate and removal efficiency at organic loads higher than 2.0 g COD/L/d. However, at hydraulic loads of 2.0 g

Table 2
Values of Dispersion Number at Various Extents of Mixing *(10)*

Extent of Mixing	Typical Values of Dispersion Number
Ideal plug flow	0.000
Small amount of dispersion	0.002
Intermediate amount of dispersion	0.025
Large amount of dispersion	0.200
Ideal mixed flow	Approaches infinity

Table 3
Results from the Tracer Studies

	Mean Residence Time t (h)	Variance s^2 (h^2)	Dispersion Number
ABR1	62.59	486.92	0.06
ABR3	46.39	1373.46	0.65

COD/L/d and below, operation with low recirculation rates was a more attractive option, because this could achieve COD removal rates and removal efficiencies that were comparable to those attained with high recirculation rates while maintaining a lower cost of operation. Tracer studies confirmed that a recirculation rate of 15 L/h, which was equivalent to recirculating the filter liquor five times per hour, was adequate in achieving effective mixing in the packed bed of the reactor.

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