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Operating strategies for aerobic fluidized bed reactors

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Abstract

This research demonstrated that an aerobic fluidized bed reactor can be operated either to maximize substrate removal, to minimize solids production or to treat intermittently produced wastewater. The operational mode is controlled by the quantity of biomass attached to the media. A thinner biomass encourages endogenous respiration and minimizes excess sludge production. Increasing biofilm thickness increases substrate removal efficiencies up to the point at which the diffusion of substrate, nutrients or oxygen becomes limiting. A thick biofilm was found to remain active even after an extended non-loading period, most likely because of endogenous respiration. Upon the introduction of substrate after the non-loading period, the substrate was immediately removed. This indicates the potential of using a fluidized bed reactor for applications that produce only intermittent wastewater flows, such as those found in many industries and hazardous waste remediation systems. © Elsevier Science B.V. 1997. © 1997 Elsevier Science B.V.

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1. Introduction

An aerobic fluidized bed reactor treating industrial and/or domestic wastewater contains a high concentration of biomass. The medium within the reactor becomes completely coated with biofilm. In contrast, the surface area of the media in packed bed reactors will not be completely coated with biofilm, nor will it be completely surrounded

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by wastewater. As a result, the time required for treatment can be an order of magnitude lower in a fluidized bed reactor when compared with a similarly sized conventional treatment process [1]. The result is a more compact reactor for a particular application.

The typical vulnerability of fixed film microbial processes to low temperatures is minimized in an aerobic fluidized bed reactor because the biomass is completely submerged in the wastewater and not exposed to the atmosphere. If granular activated carbon (GAC) is used as the support medium, its adsorption capacity for organic compounds protects the attached biofilm from shock organic loading [2,3]. GAC is also ideal for rapid biomass colonization and provides shelter from shear forces [4–6].

The quantity of biomass attached to the medium within a fluidized bed reactor largely determines the reactor's performance and, therefore, its application. Diffusion of the substrate, nutrients or oxygen into a biofilm is generally limited to depths of 0.7–120 μm [7]. When a biofilm is thick (diffusion is limiting) the substrate is degraded as rapidly as it can be obtained by the microorganisms. Further increasing the biofilm thickness has only a minimal impact on the substrate removal rate. In fact, biomass that does not contribute to substrate reduction must be removed to prevent operational problems. The most severe problem is the reduction of the density of the biomass coated medium resulting from the low specific gravity of the attached biomass. As the biomass coated medium becomes lighter it can float from the reactor and, ultimately, the entire bed can leave the reactor [1,8].

This research has examined the use of biomass controls to customize aerobic fluidized bed reactors for three different general industrial wastewater treatment applications. These applications are: to remove large quantities of substrate using a compact reactor (high rate), to minimize solids production (biomass minimization) or to treat wastewater produced intermittently (intermittent loading). Operating a fluidized bed reactor to achieve the above goals would be parallel to operating a high rate activated sludge process pre-treating industrial waste, an activated sludge extended aeration process or a sequencing batch reactor treating industrial flow produced intermittently.

2. Experimental design

2.1. Operation modes

High rate and biomass minimization applications were examined by conducting several independent reactor runs in which only practical control parameters were varied to determine their effect on performance. Control parameters that were altered were the amount of the medium, the amount of biomass removed from the medium by internal cleaning, and the substrate loading. These parameters essentially establish the amount of biomass per unit of support medium and the total quantity of biomass within the reactor. This in turn determines the biodegradation and diffusion kinetics and, consequently, the performance parameters; the removal of substrate and production of excess solids.

Nine reactor runs were conducted. One of the runs was operated in two sequential phases, where the second phase had a hydraulic loading equal to half of that in the first phase. All reactor runs had varying quantities of support medium and/or biomass

Table 1

Parameter	Independent reactor runs								
Quantity of GAC in reactor/g	30	31	35	41	61	102	127	130 [a]	149
	(1)	(3)	(3)	(3)	(7)	(3)	(4)	(8)	
	⟨4⟩	⟨5⟩	⟨2⟩	⟨6⟩	⟨23⟩	⟨15⟩	⟨18⟩	⟨14⟩	⟨12⟩
Effluent acidic acid/(mg l^{-1})	6	12	3	10	7	1	1	1	5
	(1.3)	(3.1)	(1.3)	(1.4)	(1.6)	(0.2)	(0.3)	(0.4)	(1.2)
	⟨3⟩	⟨7⟩	⟨5⟩	⟨5⟩	⟨23⟩	⟨13⟩	⟨15⟩	⟨11⟩	⟨12⟩
Effluent TSS/(mg l^{-1})	16	11	10	9	11	9	10	3	12
	(6)	(2)	(2)	(2)	(1)	(1)	(4)		
	⟨2⟩	⟨2⟩	⟨4⟩	⟨8⟩	⟨13⟩	⟨8⟩	⟨12⟩	⟨4⟩	⟨4⟩
Normalized phospholipids/	8412	4498	7531	3339	1367	2345	1415	2238	2413
(ng P/g GAC)	(931)	(675)	(791)	(299)	(134)	(519)	(243)	(142)	(280)
	⟨4⟩	⟨6⟩	⟨5⟩	⟨4⟩	⟨22⟩	⟨16⟩	⟨18⟩	⟨10⟩	⟨12⟩
Hydraulic substrate loading/ (mg min^{-1} acetic acid) [c]	7.8	7.8	7.8	7.8	7.8	7.8	7.8	3.9	7.8
Normalized substrate loading/ (mg min^{-1} acetic acid per g GAC) [b]	0.330	0.319	0.283	0.241	0.162	0.094	0.080	0.038	0.066
Normalized substrate removal/ (mg min^{-1} acetic acid per g GAC) [b,d]	0.197	0.164	0.214	0.141	0.116	0.082	0.063	0.024	0.049
Normalized TSS efficiency/ (mg min^{-1} g^{-1} GAC)	0.160	0.107	0.086	0.066	0.054	0.026	0.024	0.007	0.024

[a] Hydraulic substrate loading decreased without stopping reactor.

[b] Averaged from each set of values and not calculated from dividing the average values.

[c] The hydraulic substrate loading was calculated by multiplying the initial acetic acid concentrations by the reactor flow rate.

[d] The normalized substrate removal was calculated by multiplying the effluent acidic acid concentration by the reactor flow rate and dividing by the quantity of GAC in the reactor.

(XXX): 95% confidence interval (not provided for calculated values).

⟨XXX⟩: number of values (not provided for calculated values).

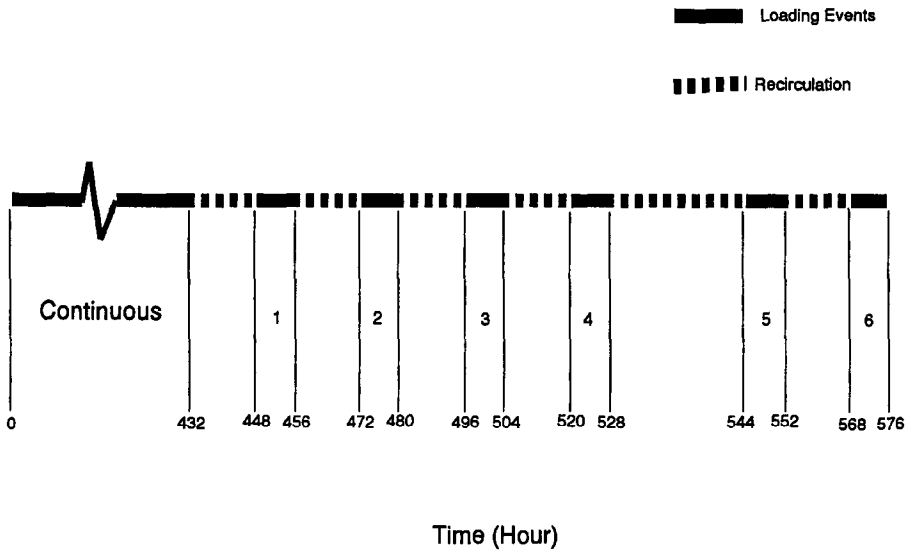

Fig. 1. Substrate loading schedule for intermittent reactor run.

attached per unit of support medium (Table 1). To compare performance, all of the evaluation parameter conditions within a single reactor run were averaged and the 95% confidence interval values were calculated after steady state conditions were achieved.

Intermittent loading was tested on a reactor run that had been at equilibrium for several weeks, so that baseline data was available. Six substrate loading events were conducted over 6 days, as presented in Fig. 1. Samples for analysis were collected before a substrate loading event and throughout the 8 h loading event.

2.2. Bench-scale reactor

Fig. 2 is a schematic diagram of the bench-scale aerobic fluidized bed reactor. The reactor was 3.8 cm in diameter and was constructed from clear PVC. An influent flow rate of 300 ml min^{-1} was used for all reactor runs. GAC (Calgon Cal, similar to F400, sieved to mesh size 16×20) was used as the support medium. The medium cleaning system (medium cleaning zone, screen washer, and bed lifter) removed excess biomass from the GAC and helped prevent plugging at the bottom of the reactor [9].

The cleaning system was located at either 58 or 92 cm from the bottom of the reactor. For very thinly biomass coated particles of support medium, the height of expansion is determined by the upflow fluid velocity. As the depth of the biofilm increases, however, the bed rises and the cleaning system determines the height of maximum bed expansion. The two locations of the cleaning system allowed the quantity of biofilm attached to the medium to vary between reactor runs, even if the same quantity of GAC was used in the runs. Cleaning to remove excess biofilm from the medium was achieved by periodically providing turbulence within the top region of the reactor so that excess biomass could be sheared from the medium. A screen that surrounded the effluent port allowed sheared

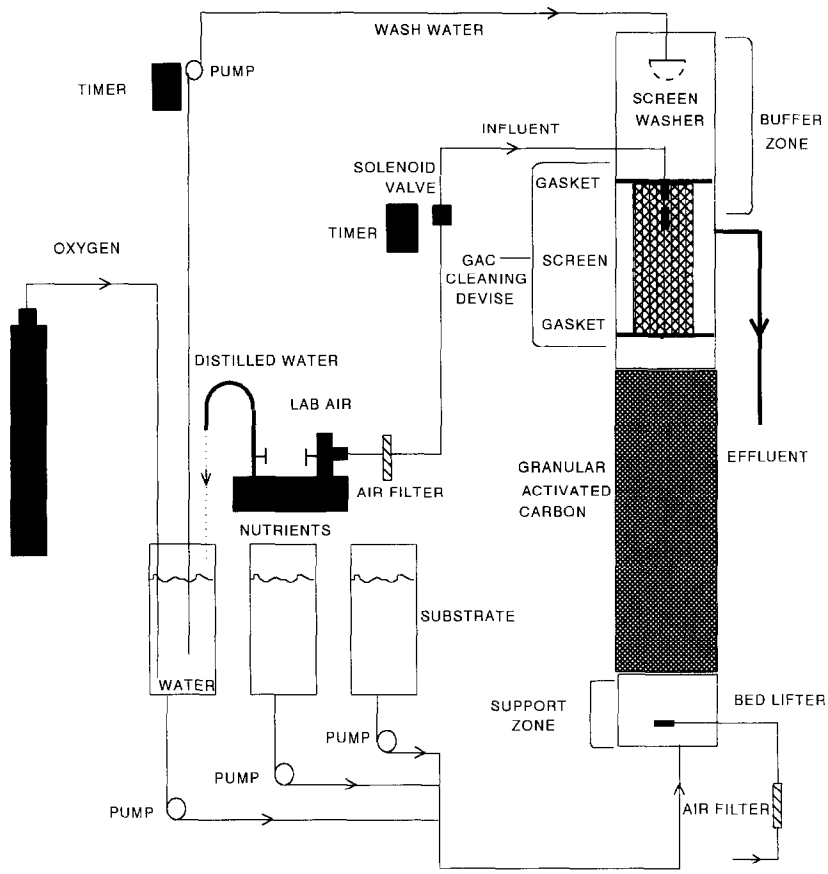

Fig. 2. Bench-scale aerobic fluidized bed reactor with internal medium cleaning.

biomass to escape from the reactor while retaining the support medium within the reactor. Using the screen washer, the screen was periodically sprayed with water to keep it free from sloughed biomass and support medium. The bed lifter created turbulence throughout the fluidized bed by continuously introducing a slow flow of coarse air bubbles at the bottom of the reactor. These bubbles facilitated transport of heavily biomass coated medium to the cleaning system so that excess biomass could be removed. More details of the cleaning system can be found in Safferman and Bishop [9] or in U.S. Patent Number 5,487,828, Safferman and Bishop.

2.3. Reactor feeds

Concentrated substrate and nutrients were prepared and stored in their own containers to prevent bacterial growth. The substrate and nutrient streams were mixed with distilled water so that the desired concentrations were obtained immediately before introduction into the reactor [9].

A standard nutrient solution was used [9]. Sodium acetate ($CH_3COONa \cdot 3H_2O$) served as the organic substrate in a simulated wastewater because it was easy to handle and analyze as acetic acid (CH_3COOH) in a gas chromatograph equipped with a packed volatile acids column. The use of actual wastewater was not deemed necessary at this stage of the research, but would be recommended in scale-up studies. The substrate hydraulic loadings for each reactor run are specified in Table 1.

2.4. Reactor evaluation

Effluent dissolved oxygen and pH were monitored to verify that they remained within the desired ranges. Flow rates were monitored and kept constant throughout the experiment.

Accurate predictions of appropriate film thickness for specific applications are difficult to obtain because of the complex interaction of biodegradation and diffusion kinetics. This is particularly true for a support medium that is not spherical and smooth. GAC has an irregular surface which results in an inconsistent thickness of biofilm. In addition, the density of the attached biofilm is not consistent with depth [10]. Consequently, the thin/thick biofilm terminology is descriptive but not that useful in describing biofilms. Biomass in this research was therefore characterized by the quantity of phospholipids [11]. Phospholipids are fatty acids that are contained in all cell walls at relatively constant concentrations [11]. They can be easily measured as phosphorus; the measurement protocol does not incorrectly include the carbon content in the support medium as biomass, extraction of the biomass from the medium is not required, and phospholipids rapidly dissipate after the cell dies [12]. Each phospholipid value reported herein is generally an average of four replicates normalized to the weight of the equivalent number of virgin GAC particles. The GAC samples used for these assays were collected from the middle of the reactor and gently washed with deionized water to remove suspended materials and loosely attached biomass. Turbulence when rinsing the medium was minimized to prevent shearing of the biomass. A phospholipid analysis of the aqueous effluent from the reactor indicated that the quantity of biomass not attached to the medium was insignificant.

Excess biosolids were measured as total suspended solids (TSS) [13]. The values reported incorporate the entire reactor operation, both cleaning and non-cleaning periods.

3. Results and discussion

Both performance and reliability for the three proposed operating strategies of the bench-scale aerobic fluidized bed system were evaluated and are discussed below.

3.1. Performance

3.1.1. High rate and biomass minimization

The two important parameters required to demonstrate that the fluidized bed reactor can be operated to either maximize the substrate removal rate (high rate) or minimize

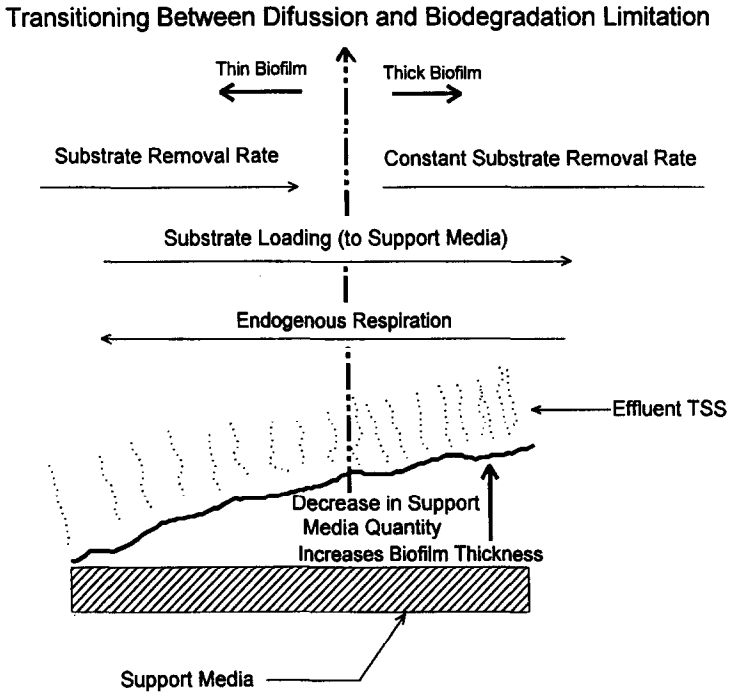

Fig. 3. Biofilm thickness operating strategies.

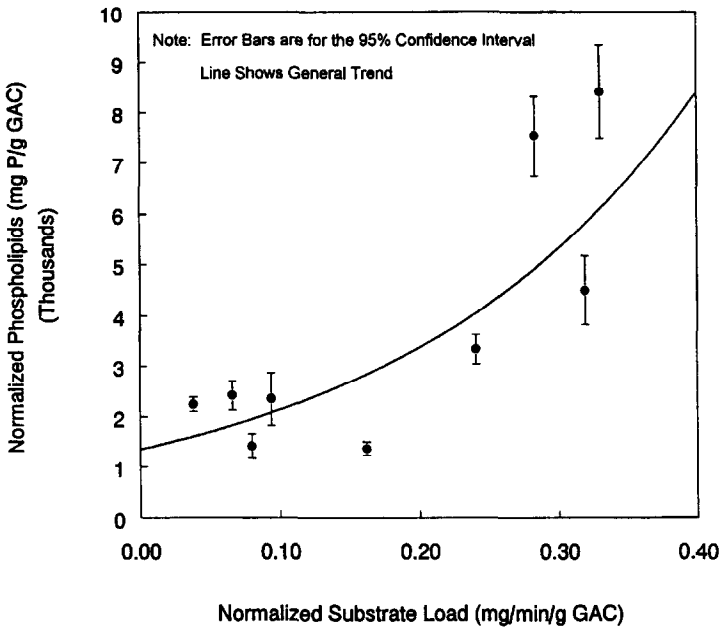

Fig. 4. Substrate loading vs. phospholipids.

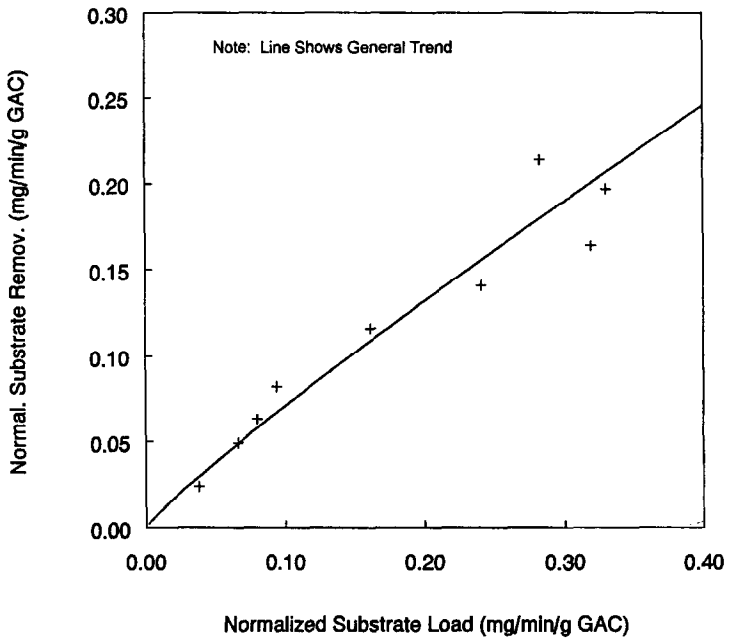

Fig. 5. Substrate loading vs. substrate removal.

biomass production are biomass per unit of support medium and substrate loading per unit of biomass. The greater the biomass per unit of medium, the greater the rate of substrate removed up to the point where diffusion becomes limiting. Beyond this thickness, significant increases in the removal rate will not occur (Fig. 3). The substrate loading per unit of medium influences the solids produced. Lower loading produces a starved biofilm and encourages endogenous respiration (Fig. 3). Biomass growth, however, is directly related to substrate loading; the higher the loading, the more biomass is produced. This was demonstrated in this research, as seen by the overall increase in phospholipids per g of GAC with increased loading to each g of GAC, Fig. 4. By recognizing this relationship, it is evident that one normalized parameter, substrate loading per unit medium (biomass/medium × substrate loading/biomass = loading/medium) can represent the different operating modes of a fluidized bed reactor. The substrate loading (mg min^{-1} of acetic acid) and the quantity of medium (g of GAC) are both easily and accurately measured and clearly show a trend relative to substrate removal and biomass production, Figs. 5 and 6. The increase in removal with increasing substrate loading (Fig. 5) levels off because diffusion of substrate, nutrients or oxygen becomes limiting. The data also demonstrates that a disproportionate increase in biomass growth (solids production) must be cleaned from the medium as the loading increases (Fig. 6). This can also be seen in Fig. 7. As the acetic acid removal rate per g of GAC increases, the amount of biomass sloughed off per g of GAC increases exponentially.

These relationships directly dictate the desired operating strategy for the fluidized bed reactor. The greater the substrate loading, the more biomass produced and the greater the

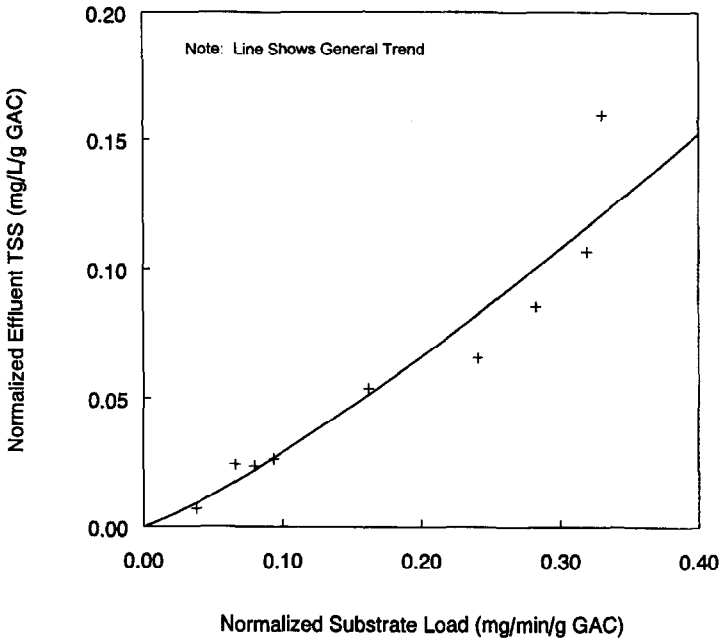

Fig. 6. Substrate loading vs. effluent TSS.

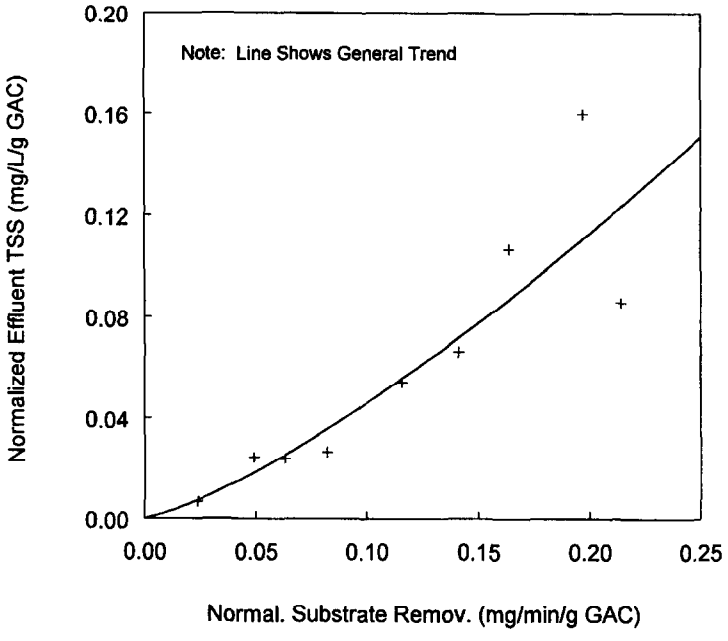

Fig. 7. Substrate removal vs. effluent TSS.

substrate removal, up to the point where diffusion becomes limiting. With lower substrate loading, less biosolids will be produced per unit amount of substrate degraded. Control of the reactor is therefore maintained by controlling substrate loading. This is achieved through recirculation of effluent with the influent to reduce loading or by controlling bed expansion with a biofilm cleaning device.

3.1.2. Intermittent loading

A fluidized bed reactor loaded intermittently would be expected to behave similarly to one operated to minimize biomass production. Of particular interest, however, is the ability of the attached biofilm to sustain its activity after a period of non-loading of substrate.

Figs. 8 and 9 present the reactor's performance during the substrate loading and recirculation periods. In each graph, the first grouping of data represents the parameter's previous steady-state continuous-feed values before the change to intermittent operation. The remainder of the groupings are for the different feeding periods during each intermittent substrate loading event. The error bars in Fig. 9 represent the 95% confidence interval for replicate samples. No measurements were taken for the first substrate loading event. Acetic acid levels in the influent and effluent were measured for

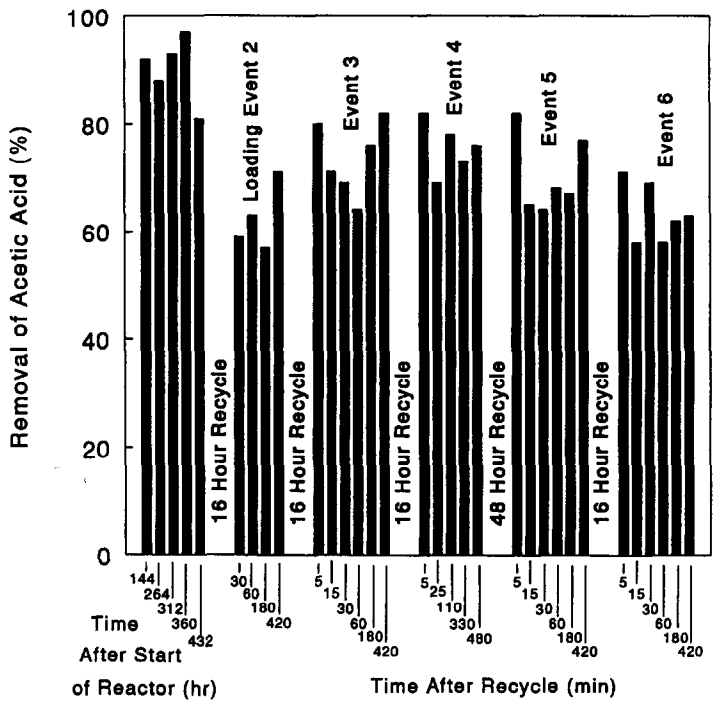

Fig. 8. Acetic acid removal efficiencies during intermittent loading.

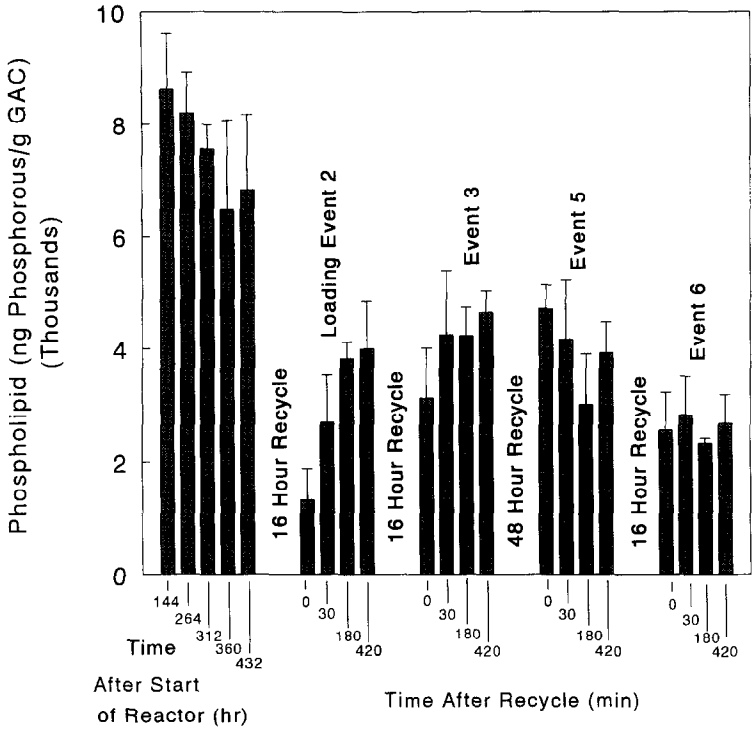

Fig. 9. Phospholipids during intermittent loading.

each of the other events. Phospholipids were measured for the second, third, fifth, and sixth events.

The acetic acid removal efficiency (Fig. 8) decreased after the first recirculation event, but the new lower efficiency remained relatively constant for the remainder of the events. This level was maintained even during the first 5 min of a substrate loading event, indicating that the population was most likely immediately activated upon substrate introduction. Although adsorption of the substrate by the GAC medium could also have been a factor, it would be expected to be minimal for these experiments because of the poor adsorption properties of sodium acetate. A similar plot for phospholipids (Fig. 9) indicates that a substantial drop in microbial population had occurred by the second substrate loading event (analyses were not conducted on the first). The level of phospholipids then remained relatively constant throughout the rest of the substrate loading events. Even within a loading period, the phospholipid level did not change substantially.

For very long recirculation periods, it is conceivable that the quantity of viable microorganisms might decrease to the point where they would be ineffective at the start of a loading event. To minimize this possibility, the reactor could be operated to grow thicker biofilms during substrate loading so that an adequate supply of excess biomass

would be available to maintain activity, via endogenous respiration, during recirculation periods.

3.2. Reliability

The internal medium cleaning system successfully prevented support medium floating from the reactor in all reactor runs. For the reactor runs that had lower quantities of biomass attached per unit of support medium, little heavily biomass coated medium reached the upper regions of the reactor for cleaning. This resulted in more trouble-free operation and reduced the chances of overloading the medium cleaning devices. As a result, less maintenance was required to prevent the particles of support medium from clinging together and clogging the cleaning zone mechanisms.

4. Conclusions

Based on this feasibility study, the aerobic fluidized bed reactor was found to be versatile and is controllable. Several common variations of the activated sludge process can be mimicked, including high rate, extended aeration, and sequencing batch reactor, at a fraction of the space of a conventional process. The very long solids retention time of a biofilm combined with the use of GAC as the support medium increases the potential for the treatment of recalcitrant industrial wastewater.

The selection of an operating strategy should consider the tradeoff between minimizing reactor size and effluent TSS. Because of the low space requirements of an aerobic fluidized bed reactor, operating to minimize excess solids has potential for many applications where an activated sludge process does not. The complexity of the microbiological and physical processes in a fixed film process, however, make the determination of the best operating strategy challenging. Pilot-scale reactors should be used to determine the operating strategy with the most potential for success.

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