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Transient Response of Flow-Direction-Switching Vapor-Phase Biofilters

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Abstract: Transient loading of vapor-phase biofilters may result in exceedence of the local reaction or mass transfer capacity of the inlet region. In such cases, higher concentrations of contaminants are carried deeper into the bed where there is less active biomass and, in some cases, breakthrough of contaminants may occur. Previous studies have demonstrated that periodic reversal of the flow direction results in improved transient-loading response. However, quantitative information on the extent of the benefit is lacking. Step function increases in toluene concentration were applied to unidirectional-flow and flow-direction-switching laboratory reactors operated in parallel. Contaminant concentration was monitored at several points along the packed beds. Relative to unidirectional mode of operation, periodic flow reversal produced a more uniform distribution of microbial reaction capacity along the length of the packed bed. Directional switching at a 12-h interval did not result in a loss of activity or removal capacity. Mass-removal rates under transient-loading conditions were similar in the first-half of both biofilters but, in the second-half of the units, significant removals were observed only in the flow-direction-switching biofilter. As a result, maximum mass-removal rates under transient-loading conditions were approximately twice as great for the flow-direction-switching biofilter relative to the conventional unidirectional-flow biofilter receiving similar mass loading.

Introduction

Limited attention has been given to the characterization and optimization of transient-loading response in biofilters used to treat air streams contaminated with volatile compounds (Deshusses 1995; Tang et al. 1995; Deshusses et al. 1996; Kinney 1996; Martin and Loehr 1996; Tang and Hwang 1997; Schroeder et al. 2000; Irvine and Moe 2001; Mysliwiec et al. 2001; Schroeder 2002). Typically, airflow rate is constant during the operation of vapor-phase biofilters and transient-loading results from variation in contaminant concentration. Most work to date has been focused on steady-state operating conditions. However, based on observations of both field and laboratory units, transient loadings are common and result in increased bed penetration or breakthrough of contaminants (Togna and Frisch 1993; South Coast Air Quality Management District 1994; Ergas et al. 1995a; Deshusses 1995; Deshusses et al. 1995, 2001; Wright et al. 1997; Irvine and Moe 2001).

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Biofilters are nominally plug-flow heterogeneous reaction processes. The microbial population density is related to the availability of substrate or nutrients and has been shown to decrease by one to four orders of magnitude between the inlet and outlet of the filter packing media when systems are operated under nominally steady-state unidirectional loading conditions (Ergas et al. 1994; Kinney 1996; Song and Kinney 2000). The microbial populations in biofilters will respond satisfactorily to transient loadings within certain boundaries of elevated concentration and length of offtime. However, at some ratio of peak to baseline inlet concentration (or, in the case of regular transients, peak to mean inlet concentration), breakthrough can be expected. Likewise, at some length of time between feed periods, breakthrough can be expected.

Attached growth biological processes, such as biofilters, are inherently unresponsive to large step increases in inlet concentration because of the distribution of microbial activity along the length of the reactor. When large transient loadings occur, either the mass transfer capacity or the reaction capacity of the initial sections of the bed are exceeded and contaminants move into the latter sections where the microbial populations and reaction capacities are low (Ergas 1995b; Wright 2004, 2005). If the step increase is sustained, contaminant removal rates will gradually increase over time as the population acclimates and increases in number. The process is slow and typically takes several days or weeks to complete (Parks and Loehr 1994; Seed and Corsi 1994; Tang et al. 1995). A corresponding process exists with respect to downtime. When a unit is shut down for an extended period of time, the microbial population begins to go dormant and increased penetration of contaminants will occur on startup. Short-term shutdowns of a few hours do not appear to affect biofilter performance upon restart (Togna and Frisch 1993; Deshusses et al. 1996; Kinney 1996; Martin and Loehr 1996; Marek et al. 2000; Park and Kinney 2001; Song and Kinney 2001; Woertz et

al. 2001). However, for extended periods of nonoperation, the initial performance upon restart can be low but the microbial population will re-acclimate with time (Kirchner et al. 1994; Tang et al. 1995; Wright 2005).

The limitations on transient-loading response are important because: (1) many desirable applications for biofilters will be at facilities having transient loadings (e.g., enterprises with variable processing rates and operating on one or two shifts per day and/or closing on the weekends), and (2) appropriate performance monitoring requirements should reflect actual operating characteristics. Currently available models cannot be used to predict transient-loading response with great accuracy because adequate characterization of the microbial population is not possible at this time (Mysliwiec et al. 2001).

Managing Transient Loadings

Approaches for minimizing breakthrough resulting from transient loadings include: (1) physical damping of fluctuating contaminant concentration, (2) feeding contaminant or surrogate compound as a supplement during extended "off periods" or periods of low inlet concentration, and (3) increasing the average reaction capacity of the biofilter. Physical damping can be accomplished by installing an upstream load-dampening unit containing absorbent liquid (Al-Rayes et al. 2001) or adsorbent solid (Weber and Hartmans 1995), or by adding absorbent/adsorbent material as a partial or sole component of the biofilter packing (Leson and Winer 1991; Hodge and Divinney 1995; Tang et al. 1995; Weber and Hartmans 1995; Campbell and Connor 1997; Irvine and Moe 2001). Performance may become limited if granular activated carbon (GAC) is used with humid waste streams because capillary condensation occurs and GAC surfaces become coated with water which reduces contaminant adsorption capacity and slows contaminant mass transfer rates to micropore regions. Feeding contaminant or surrogate compound to the biofilter as a supplement during off periods has been done successfully (Shi et al. 1995) and the approach may be reasonable if the substrate compound(s) can be stored and fed to the system economically. One study suggests that reaction capacity can be increased, relative to conventional biofilter design, by using a three-structured peat media and a drip trickling system (Wu et al. 1999). Another study suggests that biofilter reaction capacity can be increased by using concentric layers of foam media in a rotating drum (Yang et al. 2003a,b).

The average reaction capacity of a biofilter may be increased by diverting a portion of the inlet flow stream around the inlet region of the bed (i.e., slip stream or step feeding) or by reversing the direction of flow in the column at regular intervals (Kinney 1996). Maintaining a more uniform microbial population throughout the column by alternating the direction of flow would be expected to provide high levels of reaction capacity along a greater fraction of the column's length by increasing the microbial population density in the downstream half of the bed and maintaining that population in an active state. Song and Kinney (2000) demonstrated that both biomass and biomass activity decreased along the length of a unidirectional-flow (UF) biofilter and were maintained relatively constant in a flow-directional switching (FDS) biofilter. A similar finding was observed in this study and the results can be found in two related publications (Wright 2004, 2005).

The benefits derived from FDS are realized for all types of transient loading, including, step increases in contaminant loading and restart following extended periods of downtime. In both cases, relative to conventional unidirectional biofilter operation, additional reaction capacity is available when contaminants penetrate deeper into the bed as a result of those transient loadings. Flow reversal can be automated quite easily, and thus the approach may be feasible in full-scale units. Park and Kinney (2001) demonstrated some improvement in transient-loading response of a FDS biofilter with the addition of a slip-feed system. Some researchers have suggested that regular transient loading, including that provided by switching flow direction, conditions or selects for a microbial population that can respond better to transient loading than biofilters that are not subject to regular transient loading (Ergas 1995b; Campbell and Connor 1997; Damborosky et al. 1999; Irvine and Moe 2001; Woertz et al. 2001; Wright 2004, 2005). In the case of Irvine and Moe (2001), three biofilters were operated in parallel with the same average loading rate, but one unit was fed continuously while the others were fed intermittently using a regular feed-on/feed-off transient-loading pattern. The intermittently fed units responded better to shock loading (higher removal efficiencies) than was the case for the continuously fed unit. Irvine and Moe explained this result by suggesting that intermittent feeding may have produced a microbial community with a physiological state that is different from, and superior to, that produced in the continuously fed unit. Irvine and Moe reasoned that this physiological state provides an enhanced ability to sorb and store (accumulate) contaminant or high-energy compounds during shock loading, and the stored material is then utilized/degraded during rest periods. In addition the resting period may allow for metabolic activities of the microbial ecosystem to "clean up" the resting biofilm, leaving it in an improved state when feeding resumes. FDS is analogous to the intermittent, or sequencing batch, operation studied by Irvine and Moe in that alternating feast/famine sequences are introduced and the downstream sections of the biofilter receive virtually no feed and are thus allowed to clean up. Thus, if physiological advantages result from feast/famine operation, FDS would be an appropriate management strategy based on simplicity.

In addition to favorable changes in the physiological state of the biofilm, improvement in transient-loading response in intermittently fed biofilters may be partially due to improved mass transfer characteristics of biofilms that are spread out deeper into the bed rather than concentrated near the inlet. The dispersed biofilm may increase biofilm/gas interfacial area and contact time and both would increase overall mass transfer rates during transient loadings (Wright 2005). Irvine and Moe noted that the contaminant mass flow rates used in their intermittently-fed biofilters, which was greater than in the continuously-fed biofilter, caused the growth of microorganisms to extend deeper into the bed. They suggested that the presence of microorganisms deeper in the bed allowed contaminant removal to occur during shock loading that would otherwise pass through the bed untreated. In intermittently fed FDS experiments that were conducted to simulate regular transients, it was found that bed penetration increased with increased off-time interval length (Wright et al. 2005).

The primary objective of this study was to provide quantitative information on the extent of the benefit of FDS. In the work reported here, step function increases in contaminant concentration were applied to FDS and conventional UF biofilters operated in parallel. Contaminant concentration was monitored at several
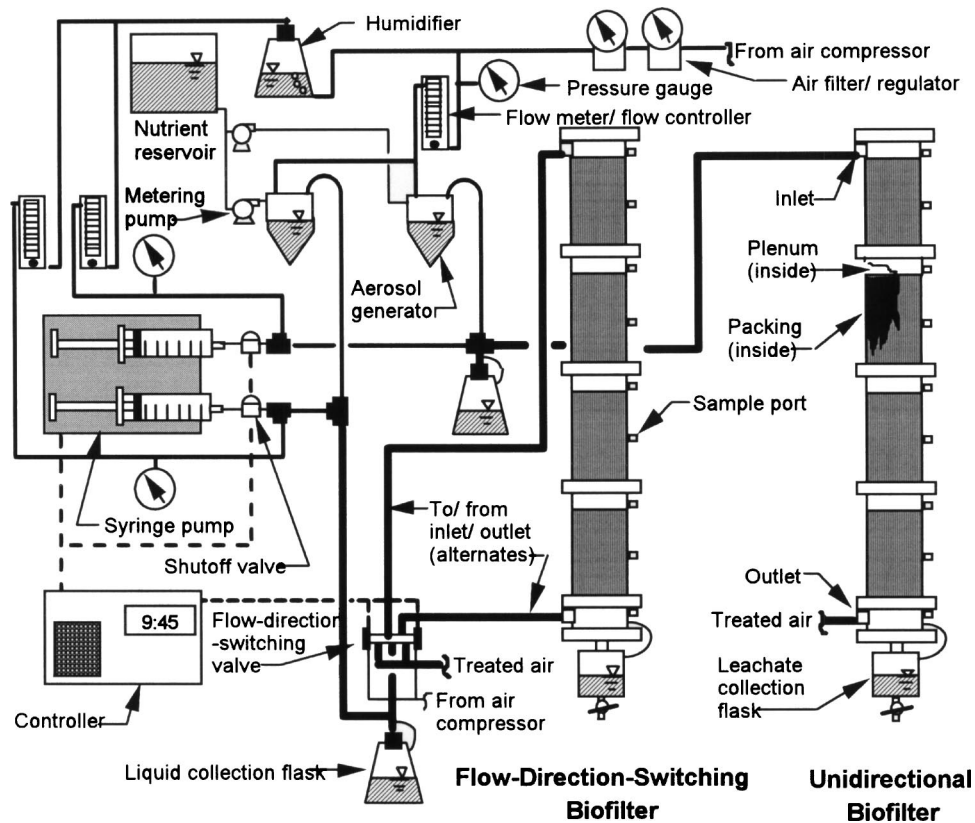
Fig. 1. Experimental biofiltration system schematic

points along the packed beds. Development of operating strategies to minimize breakthrough will allow more extensive application of vapor-phase biofiltration technology. Information developed in this study should also provide a more complete basis for establishing monitoring regulations for vapor-phase biofiltration systems.

Materials and Methods

Experimental Apparatus

A schematic representation of the experimental biofilter system is shown in Fig. 1. Laboratory compressed air was filtered through two microfiber filter regulators in series, humidified, then passed through a rotameter to measure and regulate gas flow rate. A syringe pump (Model KDS210, KID Scientific, Boston, Massachusetts) was used to deliver liquid toluene to a glass-wool wick where it evaporated into one airstream which then combined with a second airstream containing 10 μm of aerosolized nutrient solution generated by a Heart nebulizer (Vortran Medical Technology, Inc., Sacramento, California). The aerosolized nutrient solution supplied inorganic nutrients and moisture to the biofilter beds. Nutrient solution consisted of a custom recipe in which major and minor nutrients were assumed to be present in excess (Scow, personal communication, 1998). Pressure gauges were located at the outlet of the rotameter and the inlet of the Heart nebulizer. The combined airstream (containing toluene vapor and nutrient aerosol) was conveyed to the inlet of the FDS biofilter column (top or bottom depending on the cycle phase) using a

double solenoid, four-way, five-port valve (CompAir Pneumatic Model 7N504K30, Teco Pneumatic, Inc., Pleasanton, California), and electronic controller (Model XT, Chron-Trol Corp., San Diego, California). The other combined airstream was conveyed to the top of the UF biofilter column. An aerosol reduction device was installed in the UF biofilter feed system to match the aerosol removal rate of the FDS biofilter feed system (which was larger due to the presence of a five-port valve used for direction switching). Biofilter columns were constructed of 15-cm inner diameter stainless-steel pipe sections connected by Tri-Clover style joints. Each column consisted of four 25-cm long media bed sections in series separated by 5-cm deep plenums, which provided for gas-phase mixing (homogenization) of toluene vapor between media bed sections (for representative sampling and reduced propagation of channeling between bed sections). Media bed sections were supported by perforated plates. Sample ports fitted with Teflon-lined septa were located in the plenums. The media beds consisted of a mixture of new media (approximately two-thirds of the bed, volume basis) and used media (originating from a FDS biofilter used in prior experiments). The packing media was 0.64-cm diameter rigid mineral (extruded diatomaceous earth) cylindrical pellets (Celite R-635, Janus Scientific Inc., Fairfield, California). Measured pellet dimensions were highly variable with a median pellet length of approximately 0.8 cm.

Biofilter Operation and Maintenance

The biofilters operated with a nominal air-stream flux of 1 m^3/m^2 min, empty-bed residence time of 1 min and media bed temperature of 23°C. The FDS biofilter operated on a 12-h FDS

interval length throughout the study. It was found that a 12-h flow reversal interval was sufficiently short to maintain the toluene-degrading microbial community in a fully active state in related experiments (Wright 2004; Wright et al. 2005). Song and Kinney (2001) made a similar observation for a 1-day flow reversal interval, but found a 3-day switching interval was more efficient because it resulted in larger elimination capacities and greater long-term stability.

Prior to initiating the experiments, the packing media was washed with tap water, soaked in nutrient solution containing inoculum for 10 min, then brought to a pseudo-steady-state "mature" condition over a 13-day period with constant loading at a baseline inlet toluene concentration (C_0) of 107 ppm$_v$. The step-loading experiments were conducted over the next 87 days. For the purpose of this study, the term mature refers to a condition in which contaminant fractional removals in the first 25 cm of the reactor bed exceeded 85%. During step-loading events, the inlet concentration was increased for one hour. The experiment was repeated for steps concentrations of 2.5, 4, 5, 10, 20, and 50 times the baseline concentration (i.e., 268, 428, 535, 1,070, 2,140, and 5,350 ppm$_v$). Step-loading events were initiated between 3.3- and 4.7-h after the flow direction switched from upflow to downflow in the FDS unit. Transient-loading events were separated by two days or more to minimize step hysteresis (i.e., to allow reaction capacities to return to the prestep baseline level).

Bed maintenance procedures were conducted as necessary to maintain high fractional removals in the inlet region of the reactor bed. Performance in the inlet region deteriorated with time in a natural process referred to here as "aging." Aging can result from biomass clogging or local bed drying—both processes induce channeling. If not mitigated, channeling will propagate deeper into the bed and eventually lead to reactor failure (contaminant breakthrough). Loss of performance in the inlet region can also result from a lack of nutrients, or, in the case of halogen- or sulfur-containing compounds, accumulation of toxic byproducts. Oxygen limitation can be a performance-limiting factor in high-rate reactors treating soluble contaminants, but is probably not a significant factor in units operating at low baseline loading rates when treating relatively insoluble contaminants (e.g., toluene). Mass transfer and/or reaction (kinetic) limitation is more likely with the latter condition dominant when the unit is subjected to shock loading. Aging was controlled by recirculation of nutrient solution through the biofilter columns approximately once per week (range 4- to 10-days) at flow rates that ranged from 4.5- to 8.5-L/minute and a durations that typically ranged from 11.5- to 12.5-h per biofilter, except, durations of 1- and 8-h were used on one occasion each. Some biomass was removed from the bed as a result of the recirculation procedure (as indicated by particles visible in the drained liquid), and it is reasonable to assume that some biomass was redistributed within the bed.

Air-Stream Sampling and Gas Chromatography Analysis

Flow-stream grab samples were collected from column ports at the inlet and at bed depths of 12.5, 25, 50, 75, and 100 cm (outlet) using 5-cc "gas-tight" Teflon Luer-lock syringes (Series 1005, Hamilton Co., Reno, Nevada) equipped with Mininert valves and Luer needles (Fischer Scientific, Pittsburgh, Pennsylvania). Three sets of baseline samples were obtained within a 2.5-h period prior to each step-loading event (the third set approximately 20 min prior to initiating the step) and three sets of transient-loading samples were obtained during each step (approximately 6, 30, and 59 min after initiating the step). One additional set of samples were obtained for the ten-fold spike 30 min after the inlet concentration was returned to the prestep baseline concentration. Samples were analyzed for toluene concentration within 15 min by direct syringe injection into a Shimadzu (Columbia, Maryland) 14A gas chromatograph equipped with a 0.5 mL sample loop, 30-m J & W Scientific DB-624 megabore column (J & W Scientific, Palo Alto, California), and flame ionization detector (Shimadzu). Blanks were used for quality control and toluene standards of 92.6 and 491 ppm$_v$ ($\pm 2\%$) were used for toluene concentration determination. The quantification limit for toluene concentration determination was approximately 0.3 ppm$_v$.

Results and Discussion

Prior to imposing step increases in contaminant concentration, the biofilter beds were brought to a prime/mature pseudo-steady-state condition with a nominal baseline inlet contaminant concentration (C_0) of 107 ppm$_v$. Response of the conventional UF and FDS biofilters operated in parallel to 2.5-, 4-, 5-, 10-, 20-, and 50-fold step increases in C_0 are presented in four formats below. Variation of toluene concentration over time at the inlet and at five bed depths are shown in Figs. 2(a–f); profiles of fractional removal as a function of bed depth are shown in Fig. 3, plots of fractional removal as a function of step-to-baseline concentration ratio are shown in Figs. 4(a and b); and plots of mass-removal rates as a function of mass-loading rate for the full bed (100 cm) and for the first 25 cm of bed depth are shown in Figs. 5 and 6, respectively. Inspection of the data reveals that, relative to conventional unidirectional operation, periodic FDS significantly improved biofilter response in each transient-loading case when contaminant concentration was increased above approximately three times the steady-state baseline inlet concentration. The results are compared to data obtained from other toluene step-loading studies in Fig. 4(b).

Inspection of Figs. 2(a–f) reveals that greater than 85% of the prestep (baseline) toluene concentration was removed in the first 25 cm of bed depth and essentially 100% was removed by mid-depth (50 cm). Prestep data markers for the 50 cm and deeper response profiles appear as "+" markers on the horizontal axes and, therefore, are difficult to see. When step-loading events were initiated, concentration profiles within the bed increased rapidly and achieved pseudo-steady-state response within 6 min, which is the time the first samples were obtained following the start of the step. Variation in syringe pump output resulted in some variability in inlet (feed) concentration as can be seen in Figs. 2(a–f). Biofilter response profiles were similar in both biofilters during the 2.5-fold step [Fig. 2(a)] with complete removal occurring within the first 75 cm of bed depth. Reaction capacity in the first half of the UF biofilter bed was exceeded during the four-fold step [Fig. 2(b)] and contaminants were carried deeper into the bed and emerged at the outlet (average value 56.6 ppm$_v$ or 13.2% of C_0). In contrast, breakthrough was minimal in the FDS biofilter (average value 2.4 ppm$_v$ or 0.6% of C_0). The brief rise in toluene concentration at a depth of 12.5 cm observed in the UF biofilter prior to the five-fold step [Fig. 2(c)] was likely the result of a toluene pulse from unsteady syringe pump operation. During the
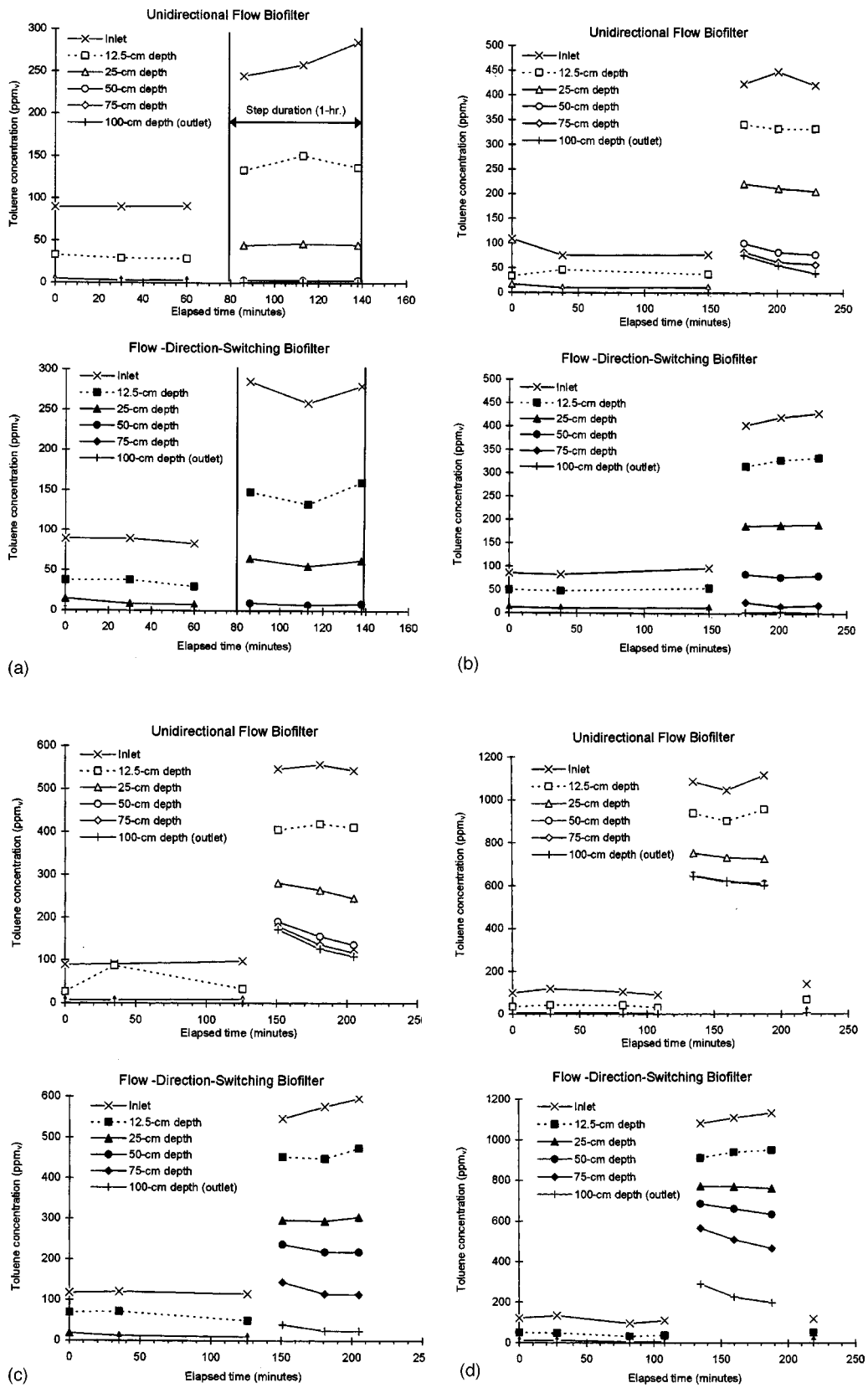
Fig. 2. Response of the conventional unidirectional-flow biofilter (top) and the flow-direction-switching biofilter (bottom) to (a) steady-state and 2.5-fold step transient loadings; (b) steady-state and 4-fold step transient loadings; (c) steady-state and 5-fold step transient loadings; (d) steady-state and 10-fold step transient loadings; (e) steady-state and 20-fold step transient loadings; and (f) steady-state and 50-fold step transient loadings. Note that in Fig. 2(f) the baseline (pre-step) response is not shown and the concentration scale begins at 4,000 ppm$_v$.
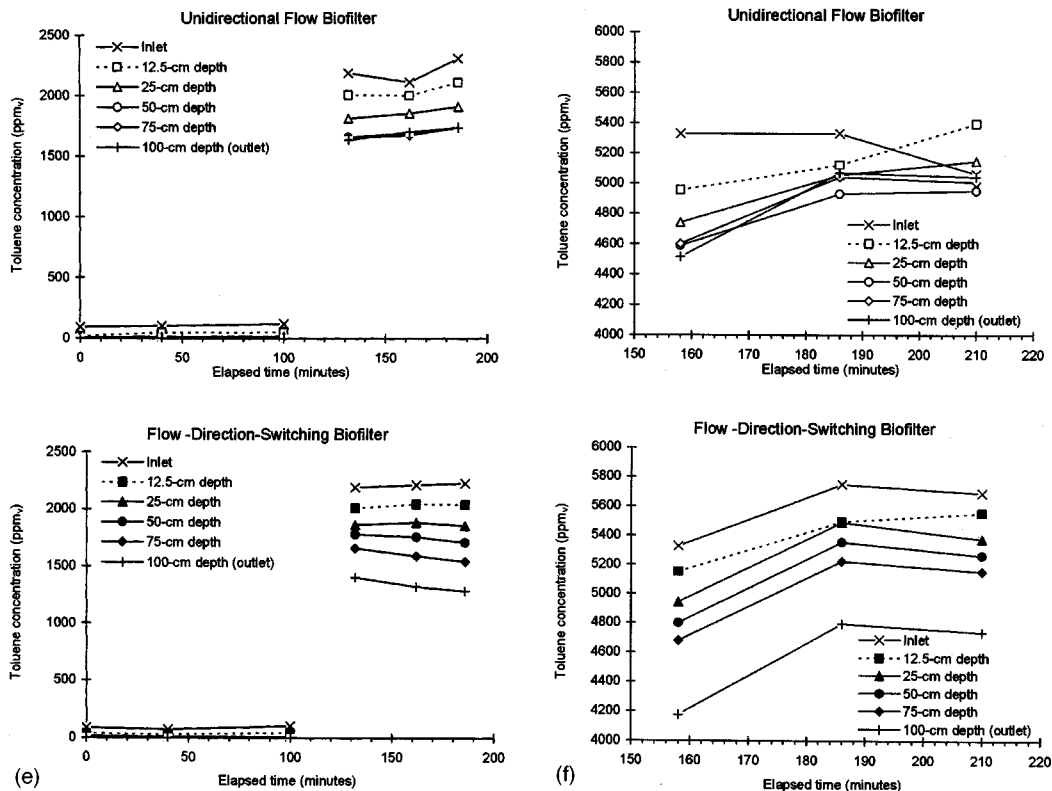
Fig. 2. (*Continued*).

five-fold step increase, toluene concentrations at mid-depth, 75 cm, and at the outlet were approximately the same value in the UF biofilter, as indicated by the overlapping curves between 150 and 200 min, because reaction capacity of the second half of the bed was minimal and additional removal was not possible. In contrast, additional treatment was possible in the second half of the FDS biofilter column and the mean contaminant concentration at the outlet was minimal (2.6% of C_0) when compared to the UF biofilter (26% of C_0). For the ten-fold and larger steps [Figs. 2(d–f)], large fractions of the feed contaminant broke through both biofilters, however, the magnitude of breakthrough was significantly less in the FDS biofilter as a result of the greater reaction capacity in that unit. Contaminant feed to the UF biofilter was unsteady during the 50-fold step when samples were taken [Fig. 2(f) top] which resulted in the scatter of response data and the appearance of negative removals in the first 25 cm of the bed. Toluene toxicity effects from the 50-fold spike were not observed when the biofilters were sampled 24 h after the spike, based on the observation that response profiles were similar to those observed the previous day immediately prior to the spike.

Significant effects of toluene sorption and desorption within the packed bed during and following transient-loading events were not evident within the time-limits/resolution of measurement procedures used in this experiment, which was 6 min at the start of the step (all experiments), and 30 min following the step (ten-fold step only). A lag in attaining elevated concentration profiles within the bed at the start of the step would indicate sorption effects, and a lag in attaining lower concentrations in the bed following the cessation of the step would indicate desorption effects. Sorption/desorption effects can be relatively minor in mature biofilters treating compounds with low to moderate solubility

in water (Campbell and Connor 1997; Al-Rayes et al. 2001), particularly when rigid/pelletized inorganic packing materials are used (Woertz et al. 2001). In contrast, sorption/desorption can be significant upon startup (or restart following extended down periods), when the contaminant is highly soluble (Deshusses et al. 1995; Campbell and Connor 1997; Al-Rayes et al. 2001), or when the packing has high organic matter content (Hodge and Divinney 1995; Tang et al. 1995; Weber and Hartmans 1995; Martin and Loehr 1996; Tang and Hwang 1997; Marek et al. 2000; Irvine and Moe 2001; Moe and Irvine 2001).

Profiles of average fractional removal across the bed for both biofilters are shown in Fig. 3 for steady-state constant (baseline) loading immediately prior to step (spike) events and for several magnitudes of step loadings. Results for the four-fold step experiment were very similar but are not shown to improve figure clarity. The solid line in each plot represents steady-state loading response profiles. Mean values were calculated from the results of the six step-loading tests (three samples per test for a total of 18 samples for each bed depth). Standard deviations of mean steady-state response values at a bed depth of 12.5 cm for the UF and FDS biofilters were 16.2 and 9.3% of C_0, respectively. Standard deviations of mean steady-state response values deeper in the bed were approximately the same magnitude in each biofilter with maximum values of 3.8, 0.2, 0.05, and 0.05% of C_0 for bed depths of 25, 50, 75, and 100 cm, respectively. The dashed lines in each plot represent transient (step) loading response profiles based on the average of three samples at each bed depth. Toluene fractional removal profiles across the UF biofilter column were nearly identical to removal profiles across the FDS biofilter: (1) in the first half (50 cm) of the bed for all loading conditions (constant and transient) and (2) throughout the full bed (100
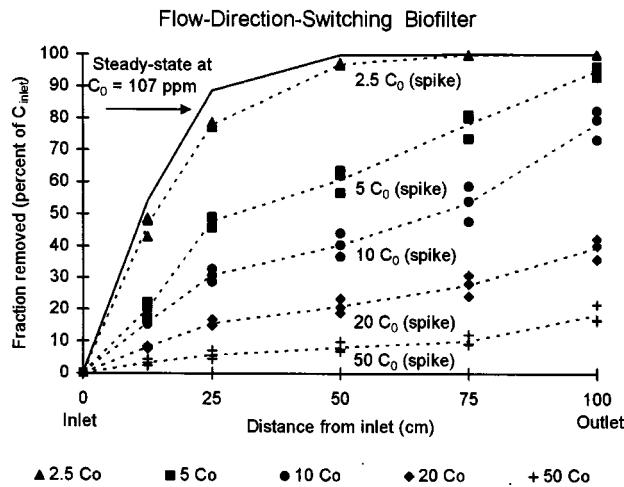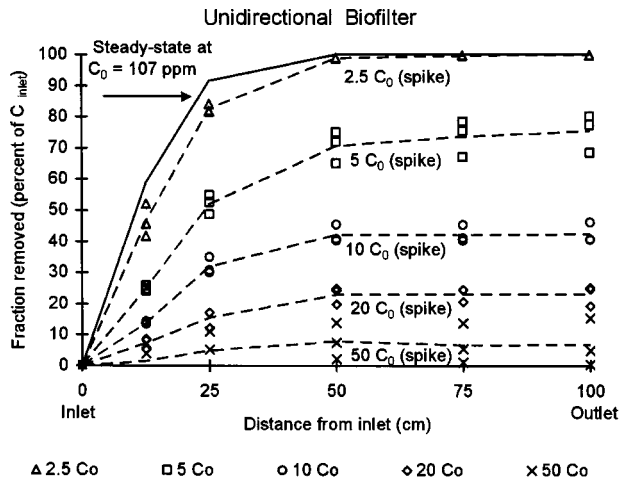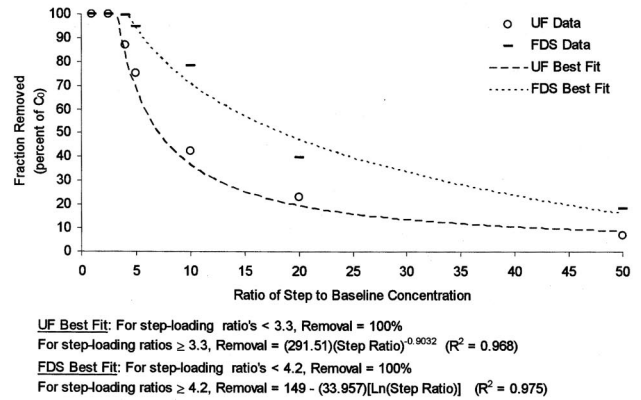
Fig. 3. Response of the unidirectional-flow (UF) biofilter (top) and flow-directional-switching biofilter (bottom) to steady-state loading (solid lines) and step transient loading (dashed lines) as functions of bed depth. The value of the third data points for the UF biofilter 50 C_0 step at bed depths of 12.5 and 25 cm (not shown) are −6.6 and −1.6%, respectively.

UF Best Fit: For step-loading ratio's < 3.3, Removal = 100%
For step-loading ratios ≥ 3.3, Removal = (291.51)(Step Ratio)$^{-0.9032}$ (R^2 = 0.968)
FDS Best Fit: For step-loading ratio's < 4.2, Removal = 100%
For step-loading ratios ≥ 4.2, Removal = 149 - (33.957)[Ln(Step Ratio)] (R^2 = 0.975)
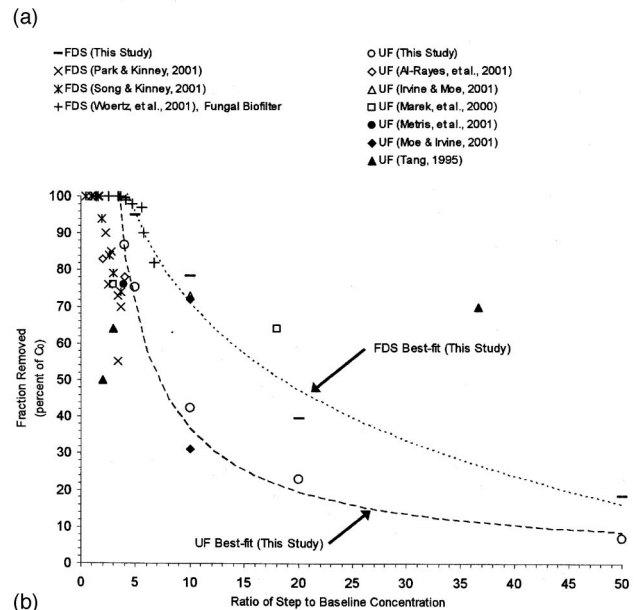
(a)

(b)

Fig. 4. (a) Relationship between fractional removal and step-to-baseline concentration ratio. The baseline toluene concentration was 107 ppm$_v$. (b) Relationship between fractional removal of toluene and step-to-baseline concentration ratio plotted with data from other studies. Design and operational parameters for the other studies are given in Table 1.

cm) for constant (steady-state) loading. Nearly identical removal profiles in the first half of the beds indicate that operating with a 12-h FDS cycle did not diminish removal rates relative to UF operation. This result is remarkable given that the average baseline loading rate in the first-half of the FDS unit was approximately half that provided to the UF unit (i.e., each end of the FDS unit did not "see" toluene half of the time because complete removal occurred in the other half of the column when flow was applied to that end). As discussed above, when the full length of the biofilter bed (100 cm) is considered the FDS biofilter performed distinctly better than the UF biofilter for step events larger than 3-times C_0. Mass removal in the FDS biofilter was 90% greater than that of the UF biofilter for the 10-fold spike, 71% greater for the 20-fold spike, and 180% greater for the 50-fold spike [however, the comparison of UF and FDS biofilter performance for the 50-fold spike is tenuous due to the large degree of scatter in the UF data near the end of the step, as can be seen in Fig. 2(f)].

Fractional removals at the biofilters' outlets are shown in Figs. 4(a and b) as a function of step-to-baseline concentration ratio. Complete removal occurred for step ratio values less than a threshold value and breakthrough occurred when that threshold was exceeded. Based on best-fit curves of post-threshold response data (power function for FDS data and logarithmic function for UF data), threshold step-to-baseline concentrations ratios for the UF and FDS configurations are approximately 3.3 and 4.2, respectively. For step-to-baseline concentrations ratios larger than a unit's threshold value, fractional removal declined in a nonlinear manner with the UF biofilter response declining more rapidly than for the FDS biofilter.

Response of conventional (unidirectional) flow biofilters to step increases in toluene concentration has been documented previously (Tang et al. 1995; Marek et al. 2000; Al-Rayes et al. 2001; Irvine and Moe 2001; Métris et al. 2001; Moe and Irvine 2001) and published data on FDS biofilter response to step increases in contaminant concentration appear to be limited to four studies by Kinney and associates (Song and Kinney 2000, 2001; Park and Kinney 2001; Woertz et al. 2001). Data and best-fit
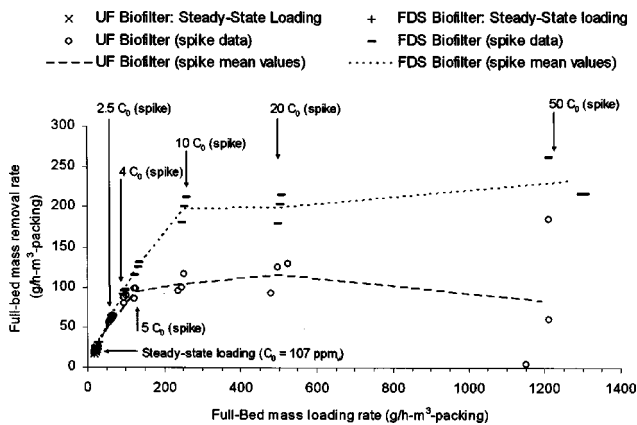
Fig. 5. Relationship between mass-loading and mass-removal rates in the full 100 cm of bed depth. Note that two data markers for the FDS biofilter 50-fold spike overlap at the far-right of the figure.

Fig. 6. Relationship between mass-loading and mass-removal rates in the first 25 cm of bed depth. The value of the third data point for the unidirection flow biofilter 50 C_0 step (not shown) is -76 g/h m^3 packing.

curves from this study are plotted together with data obtained from the other published studies in Fig. 4(b). Design and operational parameters for the other studies are located in Table 1. Data from other studies shown in Fig. 4(b) and Table 1 should be considered approximate due to limitations in obtaining accurate values from figures in the published work. When available, concentration or fraction-removed data obtained from other studies were taken at points in time when biofilter responses had stabilized and achieved a short-term pseudo-steady-state response after the step was initiated. Direct comparison of UF and FDS step-loading response relative to baseline loading can be made within this study, because the biofilters were operated in parallel from startup and the loading history prior to conducting the experiments is given (i.e., constant nominal loading rate 24.3 g/m^3 h; C_0 value of 107 ppm$_v$; air flow 0.018 m^3/min). However, direct comparison with the results of other studies has limited value because published information on those studies is incomplete, particularly with respect to loading conditions prior to the step-loading experiments (which can significantly affect the fraction of contaminant removed during step-loading events). Nevertheless, the comparison has some value and is included here.

Two of the UF step-loading studies reported removal efficiencies that were remarkably large given the magnitude of the steps. Tang et al. (1995) reported 70% removal for a 37-fold step and Marek et al. (2000) reported 64% removal for an 18-fold step. In both cases, the prestep baseline concentrations were relatively low (15 and 20 ppm$_v$, respectively) and the organic packing media would be expected to have relatively large sorptive properties. Two other UF studies, Irvine and Moe (2001), and Moe and Irvine (2001), reported somewhat large removal efficiencies for 10-fold steps (73 and 72% removal, respectively). Both studies used a polyurethane foam packing and a baseline C_0 value of 50 ppm$_v$. It is possible that, for the same step-to-baseline concentration ratio, lower values of a prestep baseline concentration could result in larger removal efficiencies than for higher baseline concentrations. For example, at lower concentrations, a larger fraction of contaminant might absorb to, or absorb in, the packing (resulting in greater removal as discussed above for polyurethane). Additional studies would be needed to answer that question. In the case of Tang et al. and Marek et al., because the
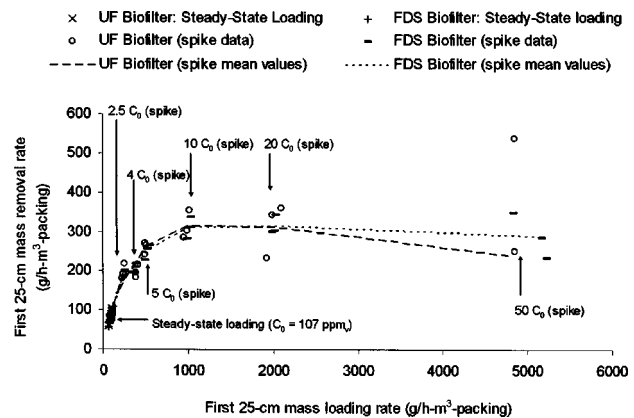
loading history of the biofilters was not reported, a third possibility is that the biofilters had received higher concentrations of contaminant than the 15 to 20 ppm$_v$ baseline concentrations indicated in the referenced articles prior to the studies, which would have supported a larger population of toluene degrading microorganisms with a greater reaction capacity at the time their step-loading experiments were conducted.

Park and Kinney (2001), using a 3-day FDS interval and baseline C_0 value of 200 ppm$_v$, imposed step increases that ranged from 1.2 to 3.7 times C_0, which resulted in removal efficiencies that ranged from 100 to 55%, respectively. Song and Kinney (2001), using a 3-day FDS interval with a baseline C_0 value of 200 ppm$_v$, imposed step increases that ranged from 1.6 to 3.6 times C_0 which resulted in removal efficiencies that ranged from 100 to 74%, respectively. Lower removal efficiencies were observed when the experiment was repeated using FDS intervals of 1- and 7-days. Woertz et al. (2001) using a fungal biofilter with a 3.5-day FDS interval and baseline C_0 value of 200 ppm$_v$ imposed step increases in C_0 that ranged from 1.4 to 6.7 times C_0, resulting in removal efficiencies that ranged from 100 to 82%, respectively. The Woertz et al. results were remarkably similar to that of the FDS biofilter used in this study. The packing media used in all of the FDS biofilter studies was rigid mineral (extruded diatomaceous earth) cylindrical pellets (Celite R-635).

The relationship between mass-loading and removal rates for the full bed (100 cm) and for the first 25 cm of the bed are shown in Figs. 5 and 6, respectively. Scales in the two figures differ because bed volumes used to calculate loading and removal rates differ by a factor of 4. Mass-removal rates increased with step magnitude and asymptotically approached maximum values. It is not known what limited the biofilter elimination capacity in this study but it is reasonable to assume that it was limited by kinetics, however, it is also possible that oxygen, a nutrient, or a waste product could have been a limiting factor in some regions of the biofilm. Once again, we see that mass-removal rates in the FDS biofilter were clearly superior to mass-removal rates in the UF biofilter for steps with magnitudes larger than approximately three times the prestep value when the full depth of the biofilter bed is considered (Fig. 5). Maximum contaminant removal rates for the full bed depth were approximately twice as great in the FDS biofilter (230 compared to 115 g/h m^3). Mass-removal rate curves in each unit were nearly identical to each other in the first 25 cm of the bed with maximum contaminant removal rates of

approximately 310 g/h m^3 packing. As discussed previously, the result of similar elimination capacities in the first 25 cm of each bed is surprising given that the effective (or average) steady-state baseline loading rate provided to the first-half of the FDS biofilter was half the value provided to the UF unit. It is reasonable to assume that, at the levels of baseline contaminant loading used here, larger loading to the UF biofilter should support a larger population of toluene-degrading microorganisms (and therefore have resulted in a greater elimination capacity). This result may provide additional evidence that regular transient-loading conditions, or selects for, a microbial population that can better respond to transient loadings.

Conclusions

1. Using a directionally switching mode of operation in vapor-phase biofilters results in greater removal rates in the downstream bed sections and a greater capacity to respond to transient loadings.
2. FDS at a 12-h interval did not result in the loss of activity or removal capacity in the inlet section of the biofilter.
3. Mass-removal rates under transient-loading conditions were similar in the first-half of both biofilters but, in the second-half of the units, significant removals were observed only in the FDS biofilter. As a result, maximum mass-removal rates under transient conditions were approximately twice as great

Table 1. Data from Laboratory-Scale Step-Loading Studies that Used Toluene as the Model Contaminant

Study	Flow direction mode	Media	Empty-bed contact time (s)	Baseline inlet concentration (ppm$_v$)	Step-to-baseline inlet concentration ratio	Step duration (h)	Fraction removed (% C_0)	Pretest loading history given?
Park and Kinney (2001)	3-day FDS	Silicate pellet	60	200	1.2–3.4	1.0	100–55	Yes
(data from two phases of one study)	(with slipstream)	(Celite R-635)	60	200	1.5–3.7	1.0	100–70	
Song and Kinney (2000)	3-day FDS	Silicate pellet (Celite R-635)	60	200	1.75	2.0	See[a]	Yes
Song and Kinney (2001)	3-day FDS	Silicate pellet (Celite R-635)	60	200[b]	1.6–3.6[b]	2.0	100–74	Yes
Woertz et al. (2001) (fungal biofilter)	3.5-day FDS	Silicate pellet (Celite R-635)	60	200[b]	1.4–6.7[b]	4.0	100–82	Yes
Wright et al. (this study)	0.5-day FDS	Silicate pellet (Celite R-635)	60	107	2.5–50	1.0	100–18	Yes
Al-Rayes et al. (2001)	UF	Compost-isolite-limestone	44	175	4.0	2.0	78	Yes
(data from two phases of one study)			53	185	4.3	2.0	83	
Irvine and Moe (2001)	UF	Polyurethane foam	120	50	10	1.0	73	Yes
Marek et al. (2000)	UF	Peat-bark-wood	30	20	3	1.0	76	No
(data from two phases of one study)			60	20	18	1.0	64	
Métris et al. (2001)	UF	Perlite-compost	60	122	3.9	6.0[c]	76	No
Moe and Irvine (2001)	UF	Polyurethane foam	120	50	10	1.0	72	Yes
(data from two biofilters operated in parallel)			120	50	10	1.0	31[d]	
Tang et al. (1995)	UF	Chaff-compost	150	13.6	37	156	70[g]	No
(data from two biofilters;			150	497[f]	1.8	180	50[g]	
one with two phases of study)[e]		Granular activated carbon-compost	150	505	2.8	320	64	
Wright et al. (this study)	UF	Silicate pellet (Celite R-635)	60	107	2.5–50	1.0	100–7	Yes

Note: Data obtained from other studies should be considered approximate values. FDS=flow-directional switching; UF=unidirectional flow.

[a]Song and Kinney (2000) using UF and FDS biofilters operated in parallel reported that breakthrough occurred in the UF biofilter for a 1.75-fold step of toluene while breakthrough did not occur in the FDS biofilter. The fractions removed were not reported.

[b]C_0 was increased stepwise.

[c]C_0 was increased over a 1-h period and then held constant for 6-h.

[d]Nitrogen limitation was cited as the reason for low fractional removal in the second biofilter.

[e]Response of a third biofilter, with diatomaceous earth-compost media, was reported to be similar to that of the chaff-compost biofilter.

[f]The first step raised C_0 from 13.6 to 497 ppm$_v$ over a 12-h period and it was held at that level for approximately 6.5-days, then a second step raised C_0 from 497 to 885 ppm$_v$ over a 12-h period and it was held at that level for approximately 7.5-days.

[g]Removal efficiency values were taken when the response profile reached a pseudo-steady state (approximately 60- to 80-h after the step increase was initiated).

for the FDS biofilter relative to the conventional UF biofilter. Development of operating strategies to minimize breakthrough will allow more extensive application of vapor-phase biofiltration technology. Information developed in this study should provide a more complete basis for establishing monitoring regulations for vapor-phase biofiltration systems.

Acknowledgments

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