Resolving Operational and Performance Problems Encountered in the Use of a Pilot/Full-Scale Biotrickling Filter Reactor

Todd S. Webster*, Huub H.J. Cox and Marc A. Deshusses
Department of Chemical and Environmental Engineering, University of California, Riverside, CA 92521

A pilot/full-scale biotrickling filter reactor experiment was performed at an industrial site to treat styrene laden waste gas. The engineered system consisted of two stainless steel tanks in series, each with filter bed volumes of 4.0 m^3, filled with 3.5-inch plastic spheres. The system treated 340 m^3 h^{-1} of air laden with styrene concentrations ranging up to 0.8 g m^{-3}. Over the five-month study, styrene elimination was demonstrated up to 24 g m^{-3} h^{-1} (35 g m^{-3} h^{-1} across the first tank in series) with 70 to 85% removal. Operational and performance problems were identified that differ from those developed under controlled, laboratory set-ups. Operational problems typically involved equipment malfunctions, with the most prone to failure pieces of equipment being the air sampling system and water level sensors. Performance problems were identified that possibly limited the styrene removal. The transient operation of the plant, producing discontinuous, unsteady-state concentrations, made it difficult to establish a stable biofilm on the packing material. Experiments were performed indicating both biological and mass transfer limitations may have occurred.

INTRODUCTION

The treatment of industrial air phase contaminants has predominantly been performed through the use of incineration and/or carbon adsorption. Incineration is effective for concentrated waste streams that require a minimal fuel source. However, this technology becomes increasingly expensive when treating dilute waste streams, requiring the addition of supplemental fuel. Incineration also generates secondary pollutants such as nitrogen oxides. Carbon adsorption is effective for both dilute and concentrated waste air streams, but the technology simply transfers the contaminant from the air phase to the solid phase. This solid phase is a hazardous waste and must be treated as such. Alternative technologies that have recently gained more interest in the United States are the use of biofiltration and biological trickling filtration [4, 6, 13]. With biological trickling filtration technology, a stream of contaminated air and water is passed through an inert filter bed on which a consortium of microorganisms lives. As the air passes through the bed, aerobic oxidation of the contaminant is performed and carbon dioxide, water, and additional biomass are produced. In comparison to a biofilter, a primary advantage of the biotrickling filter is the better system control of environmental conditions affecting removal performance (e.g., pH, nutrients, salts, etc.).

The treatment of air phase contaminants with the use of a biological trickling filtration reactor is relatively new in the United States. Hence, a paucity of knowledge is available detailing problems associated with the technology operating in an industrial setting. Recent papers have explored nutritional limitations and bioclogging problems associated with biotrickling filters [8, 10, 11, 12]. However, these studies have been performed in laboratory or controlled environments. This article describes some of the necessary problem solving and "trouble-shooting" required in the operation of a pilot- or full-scale biotrickling filter reactor at an industrial facility. Two types of problems are detailed in length: operational and performance problems. Operational problems involve those instances where system operation is impeded or halted. This type of problem is a function of system equipment malfunctions, operator error, and site-specific malfunctions. Performance problems are those that lead to inadequate system contaminant removal. Performance may be affected by nutrient limitations, temperature fluctuations, transient operating conditions, channeling of air, microbiological limitations, as well as a result of operational problems. Both prob-

*Todd S. Webster is now with Envirogen Inc.,
4100 Quakerbridge Road, Lawrenceville, N.J. 08648.

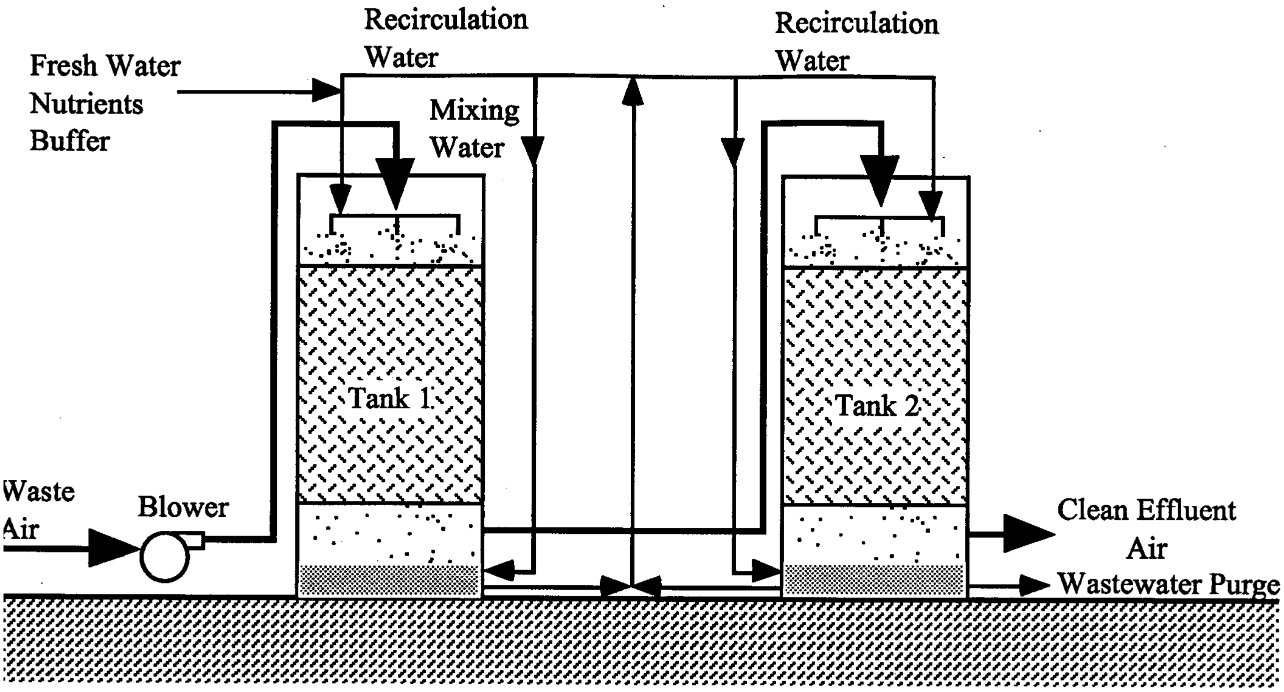

FIGURE 1. Schematic of the biotrickling filter system. For this cocurrent system, air is passed through the two tanks in series and water is applied in parallel.

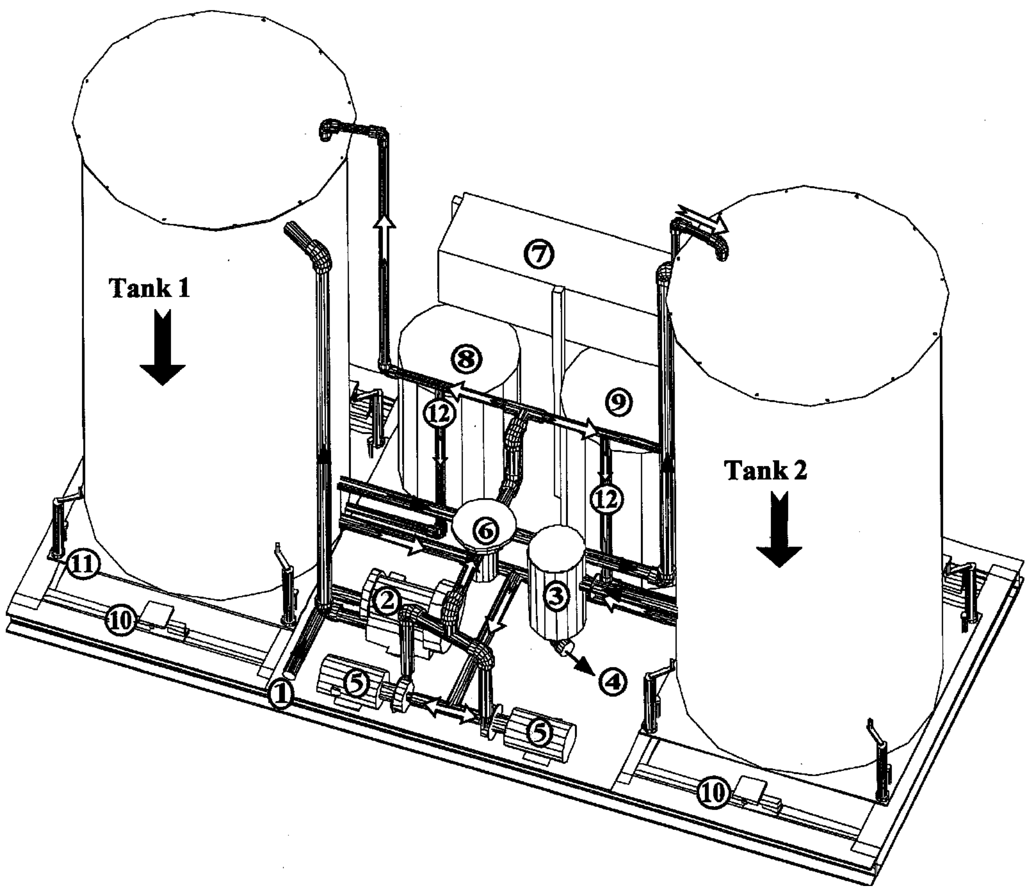

FIGURE 2. Design drawing of the pilot-scale biotrickling filter reactor. Open arrows: water flow; filled arrows: air flow. (1) contaminated inlet air; (2) blower; (3) knock-out pod; (4) purified outlet air; (5) water pumps; (6) strainer basket; (7) computer control box; (8) nutrient tank; (9) caustic tank; (10) sliding load cells (outside position); (11) jacks; (12) water return to tank bottoms (for mixing).

lem types are explained and resolutions noted where improvements might or have been implemented.

Process Description

In an air phase biological trickling filter reactor, waste gas contaminants are absorbed in a flowing liquid phase and biodegraded by suspended and immobilized microorganisms (Figure 1). Depending on the specific operation, the reactor operates with either co- or countercurrent movement of the air and water phases. The flowing water phase benefits the biotrickling filter by providing a continuous supply of nutrients, removing possible degradation by-products, suspending biomass for continual reseeding of the system, and aiding in the diffusion of hydrophilic pollutants into the biofilm. As the water is recirculated over the packing material, an operator or computer may add nutrients, acids, or bases to aid in regulating the environment for optimal contaminant removal. It is essential for the system to host a thriving microbial population while avoiding clogging conditions.

Removal of the contaminant in the reactor occurs by microbial catabolic reactions within the fixed biofilm, and to some smaller degree, in the liquid phase by the suspended microbial consortium. Contaminants enter in the gas phase and are absorbed into the biofilm attached to the inorganic packing material. The microbes convert the contaminant, along with oxygen, to carbon dioxide, water, and additional biomass. Because some contaminants are more recalcitrant, complete oxidation may not occur and intermediates may form. These intermediates may pass through the remainder of the system untreated. Additionally, some compounds can form end products that are harmful to the sustainability of the microbes. For instance, during the degradation of some chlorinated or reduced sulfur compounds, acidic metabolites may form and cause the pH of the recirculating water to rapidly decline. This rapid decline will inhibit the performance of the microbes if not properly resolved. Biotrickling filtration is an effective technology for those contaminants that are considered biodegradable. For those contaminants which can not be completely oxidized or resist any degradation whatsoever, further physico-chemical treatment may be required.

EXPERIMENTATION AND METHODS

Site Description

The test site was located at a fiberglass bathtub manufacturing facility (LASCO Bathware, Anaheim, CA). The pilot-scale biotrickling filter was operated for five-months. Styrene vapors were emitted from the plant during the manufacturing process through a stack at a flowrate of 51,000 m^3 h^{-1} and at concentrations up to 0.8 g m^{-3}. The waste gas was emitted at a temperature of 25^{o}C and did not contain other contaminants. All particulates were removed prior to entering the stack by a filter screen. The plant generally operated continuously Monday morning through Saturday morning. It was shutdown over the weekend.

Reactor Design

The pilot-scale reactor design was based on three successful years of operation of a bench-scale biotrickling filter at the Swiss Federal Institute of Technology [14]. The prototype system, designed and constructed by the University of California at Riverside and Environmental Biosystems (Sandwich, MA), included two side-by-side tanks constructed of 304 stainless steel, each with an internal diameter of 1.6 m and height of 3.4 m (Figures 1 and 2). Each tank had filter bed height of 2.0 m, consisting of Jaeger Tri-Pack® (Houston, TX) spheres with a diameter of 8.9 cm and a specific surface area and void space of 125 m^2 m^{-3} and 95%, respectively. The bed volume per tank was 4.0 m^3.

Standard Operation

The biotrickling filter reactor was set up to withdraw a side stream (340 m^3 h^{-1}) of styrene-contaminated air from one of the facility stacks for treatment, giving an empty bed retention time of 43 seconds per tank. The flow remained constant throughout the experimental study. The reactor system utilized one blower (pressure), two water pumps, and two water heaters to deliver air, water, and heat, respectively. The blower supplied the waste gas through stainless steel piping (3 inches in diameter) to the tops of the two tanks in series.

The pumps sprayed water in parallel to the two tanks through Schedule 40 and 80 PVC piping (diameters of 1 to 3 inches) at flowrates up to 400 liters per minute each. A portion (114 liters per minute) of the total recirculating water was directed to the base of each tank to provide adequate mixing of the tank bottom. A volume of 0.8 m^3 of water was maintained in the base of each tank. This served as a water reservoir to control pH and other water parameters. A water level observation tube was connected with vinyl tubing to two separate locations outside each reactor tank. One of the connections was to the base of the tank (below the water line), while the other was connected above the water line. Float level sensors inside the tube detected changes in the tank water level. The reactor also contained a water strainer basket to remove large particulates from the recirculated water and a knockout pod to remove air phase particulates and water from the effluent air.

The nutrient and caustic were stored in 757 liter tanks and supplied periodically through 1.3 cm ports on the pressure side of the water piping. Using two diaphragm nutrient feed pumps, a GrowMore hydroponic premixed fertilizer (Gardena, CA) containing 12/9/11 mass percentage of N/P/K and the trace elements iron, magnesium, calcium, zinc, copper, manganese, and sulfur, was added to the recirculation water at a feed concentration of 0.7/0.5/0.6 g l^{-1} of N/P/K. Two diaphragm feed pumps metered a caustic solution of 5% NaOH into the recirculation water to maintain the pH between 6 and 8.

A programmable logic controller (PLC) unit, programmed using Labview Software (National Instruments, Austin, TX), was implemented to monitor and control important parameters such as inlet and outlet concentrations, air and water flowrate, nutrient and caustic addi-

TABLE 1. Biotrickling Filter Operational and Performance Parameters Measured Using a Programmable Logic Controller Computer With Feedback Control Capabilities.

Parameter to Be Measured	Type of Instrument	Notes
Air Flowrate	Orifice Plate (Differential Pressure)	Differential pressure used to calculate flowrates. Located downstream of blower before tank 1.
Air Phase Concentration	Flame Ionization and Direct Electrolytic Conductivity Detectors (FID/DELCD Detectors)	Air measured at inlet, between, and outlet of two tanks. Also, set up to measure concentration along the length of each tank.
Air Pressure	Pressure Gauges (Electronic)	Measured across both tanks, the blower, and the entire system.
Air Temperature	Thermocouples	Air measured at inlet, between, and outlet of two tanks. Also, set up to measure temperature along the length of each tank.
Tank Weights	Load Cells	Three load cells per tank.
Water Conductivity	Conductivity Probe	Measured after water pumps.
Water Flowrate	Paddlewheel Flow Sensors	Measured at the inlet of both tanks.
Water Level Indicators	Water Float Sensors	Measured outside of each tank in a water level observation acrylic tube.
Water pH	pH Probes	Measured directly in each tank.
Water Pressure	Pressure Gauge (Electronic and Analog)	Measured in-line on pressure side of pumps.
Water Temperature	Thermocouples	Measured at the outlet of both tanks.

tion, water addition and removal, pressure drop, temperature, pH, and conductivity. The PLC used feedback control logic to maintain the operating parameters of the reactor to within specified input limits. Specific methods used to measure many of the parameters are listed in Table 1.

The system was inoculated with a concentrated mixed culture of microbes extracted from a dissolved air flotation unit from a publicly owned treatment works. This culture was added to the recirculating water along with a nutrient solution to promote growth. The reactor recycle liquid was initially operated in a batch mode of operation for two weeks to promote bacterial attachment to the packing. Contaminated styrene vapors from the stack were supplied to the system at an average mass load of 26 g m^{-3} h^{-1} (during initial month of operation the average load was 20 g m^{-3} h^{-1}). During the batch mode of operation, the system performance was monitored. Continuous, improving performance indicated sufficient biological activity and provided evidence to operate the recycle liquid in a continuous mode. The continuous mode of operation involved the hourly removal of 10 liters of recirculation water and the replacement with 10 liters of a fresh nutrient solution.

The focus of the experiment was to optimize pollutant removal while assessing various operational and performance problems under an industrial setting. Over a five-month period, operational problems that created system malfunctions were noted and solutions were engineered. The effects of environmental reactor conditions, transient operating conditions, air channeling problems, and microbiological limitations were assessed to improve reactor performance.

RESULTS AND DISCUSSION

Resolving Operational Problems

In general, problems of a newly operating biotrickling filter can be numerous. These operating problems cause or lead to component malfunction or complete system shutdown. System shutdown is detrimental to performance and can have grave economic impacts at the full-scale level. Hence, assessment of the problems that cause system shutdown is warranted. The most common operational problems observed during the experiment and their frequency have been classified under system component malfunctions and industrial site upsets (Tables 2 and 3).

System Component Malfunctions

System component malfunctions occurred numerous times during the progression of the experiment. Though some problems were attributable to design or construction constraints, others were simply maintenance problems that every large system is bound to have. Of the system component malfunctions, three notable problems that were not foreseeable in the

TABLE 2. System Component Malfunctions, Their Effect on the System, and Resolution of the Problems (Over a Period of Five Months).

Component Malfunction	Frequency	General Problem	Result/Effect On System	Resolution
Water Level Indicators	6	Mechanical float level indicators often were impeded by biomass build up on the float.	Created a situation where PLC system failed to recognize the water level declining. Eventually (approximately 2 days), the water level in the reactor declined below the tank water outlet, causing air to be pumped in the line and the system to shut down.	Level indicators were frequently cleaned. Surface contact area for the float was reduced. Suggest capacitance based level indicators for better effective control of turbid water levels.
Sampling System (FID Flame Out)	6	As a result of large backpressure generated by the knockout pod, water and biomass became entrained in sampling lines and entered the sampling system and FID.	Caused sampling system failure (constant FID flameouts) and prevented reliable concentration data acquisition for over two weeks.	Sampling pump diaphragms were cleaned and lines manually cleared. Sampling pump operated at less capacity compared to prior operation. Diaphragms needed replacement. Lines should be visually inspected for water on a daily to weekly basis.
Nutrient Pumps	5	Pumps failed to prime when air was in line. Nutrients would precipitate and clog inlet port to reactor.	The system failed to receive nutrients for short periods of time (1-2 days).	Ports were manually cleaned and nutrient solution was adequately mixed to enhance solubility. Ports and lines should be checked on a weekly basis.
Unknown System Problems	5	Unknown problems caused low water pressure alarms to be set off. May have been facility electrical problem.	System shut down.	System restarted.
Water Level Observation Tube-Air Inlet Line Clogged	3	A water level observation tube is connected by two lines to the side of each tank. The differential presure between the line at the bottom (filled with water) and top (filled with air) physically moves the water level. Water from the tank would get into the air line. Biomass accumulated and event-tually clogged the line (in 2-3 days).	When the upper air line became clogged, a huge differential pressure developed in the obser-vation tube. This caused the water level to quickly rise and give a false reading of a high water level situation to the PLC. The PLC shut the system down.	A long tube was attached to the air line and inserted downward into the sidewall of the tank. Water (or biomass) trickling down the inside of each tank could not enter the tube that was also pointed downward.
Knockout Pod	3	Pod would collect water and biomass slowly grew on filter over time. Backpressure in the system increased to maximum levels.	System shut down because of large pressure differentials.	Knockout pod should be checked and cleaned on a weekly basis. Filter will need replacement every four to five months.
Air flowrate miscalculated by PLC	1	A pressure line used to measure differential pressure across an orifice plate broke.	The air flowrate was erroneously calculated to be much lower than the actual flowrate. The PLC ack-nowledged this low flowrate phen-omenon to be a mechanical failure in the system and correctly shut the system down (3 days).	The pressure line was replaced and the air flowrate was once again calculated correctly by the PLC.
Water Pump/Relay	1	Faulty electrical wiring hook-up caused a short with the water pump relay, causing an electrical overload on the water pump.	System shut down.	The second pump was used alone, temporarily. Defective pump was removed and repaired. Wiring was replaced.
Piping Cracked	1	Schedule 40 PVC inlet water line cracked.	Water was discharged for a small period of time on reactor, but had no effect on operation of reactor.	Part replaced and no further piping problems observed.

TABLE 3. Industrial Site Specfic Upsets, Their Effect on the System, and the Resolution of the Problems (Over a Period of Five Months).

Site Upsets	Frequency	General Problem	Result/Effect On System	Resolution
Resin Development in Line	3	Unknown source of resin somehow entered air inlet line to blower.	No effect. Resin did not appear to reach blower but could be a problem if not detected	Remove resin from line before it enters the blower. Check for resin development once a week.
Electrical Malfunction	2	Power outages and site-employee mistakes caused electrical system to be disconnected.	System shutdown	System restarted and signs added to electrical lines to warn employees against disconnecting electrical lines.
Water Addition Malfunction	1	Site employees mistakenly disconnected water line to reactor.	System failed to get fresh replacement water for lost evaporative water. Eventually (approximately 2 days), the water level in the reactor declined below the tank water outlet, causing air to be pumped in the line and the system to shut down.	Water turned back on.

design phase of the system occurred during operation. The first operational problem was that the water level float sensors, used to indicate the level of the water in the biotrickling filter reactors, consistently failed because of suspended biomass. The suspended biomass caused the floats to stick to the observation tube wall. The floats required regular cleaning, but the procedure was time consuming. Capacitance based level sensors could potentially be a better choice, since they eliminate the need for a float.

Another component malfunction developed with the system knockout pod located at the end of the treatment train. The purpose of this pod was to collect and return water that exited the reactor vessel in the effluent air, as well as to filter any particulates that may have been emitted in the process. Little to no particulates were observed on the filter, but humidified air created a suitable environment on the knockout pod filter for microbial growth. This growth caused large pressure drops (increased 25 to 50% compared with the clean pod pressure drop) over the entire reactor system, eventually shutting the system down. From the detection of this problem, it is advisable to clean the filter once a week and replace it every three to four months. Even so, knockout pods present large pressure drops (can increase system pressure drop 25% for a clean pod) and depending on the reactor setup, their use may not be required or other systems (demisters) may be better suited.

The gas sampling system with the FID had numerous problems near the end of the experiment (Day 120). The system was designed so that if small amounts of water condensed in the sampling lines, the gas-sampling pump would remove this condensation by backflushing the sampling lines every fifteen minutes. Such a procedure was regulated through the PLC computer and was effective. However, a rare case occurred where some large backpressures were caused in the air distribution lines by the clogged knockout pod. These large backpressures forced sludge and water into the gas sampling lines and through the gas sampling system. The operator cleaned the sampling system, but the gas-sampling pump was damaged and the capacity was significantly reduced. This reduction in capacity limited its backflushing capacity as well, allowing condensation to enter the FID, causing repeated flameouts. The diaphragm in the pump required replacement. A sampling system that can draw sample gas into the FID and then backflush the line is very effective if not hindered by other problems. If the reactor is in cold climates, using heated sampling lines may also be used to prevent condensation. For a more effective condensation prevention system, incorporation of both heated lines and backflushing is advisable. In order to prevent significant operational problems from occurring, sampling lines should be checked regularly (once a week) for water condensation and biomass build-up.

Numerous system components, whether water, air, or sampling, demonstrated some problems during the five month study. As is the case with most prototype

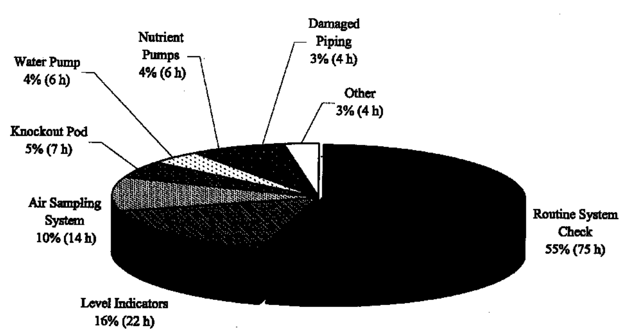

FIGURE 3. The distribution of time (% and hours) required for routine system checks and maintenance on different malfunctioning systems over a five-month operating period. Total hours = 138 h.

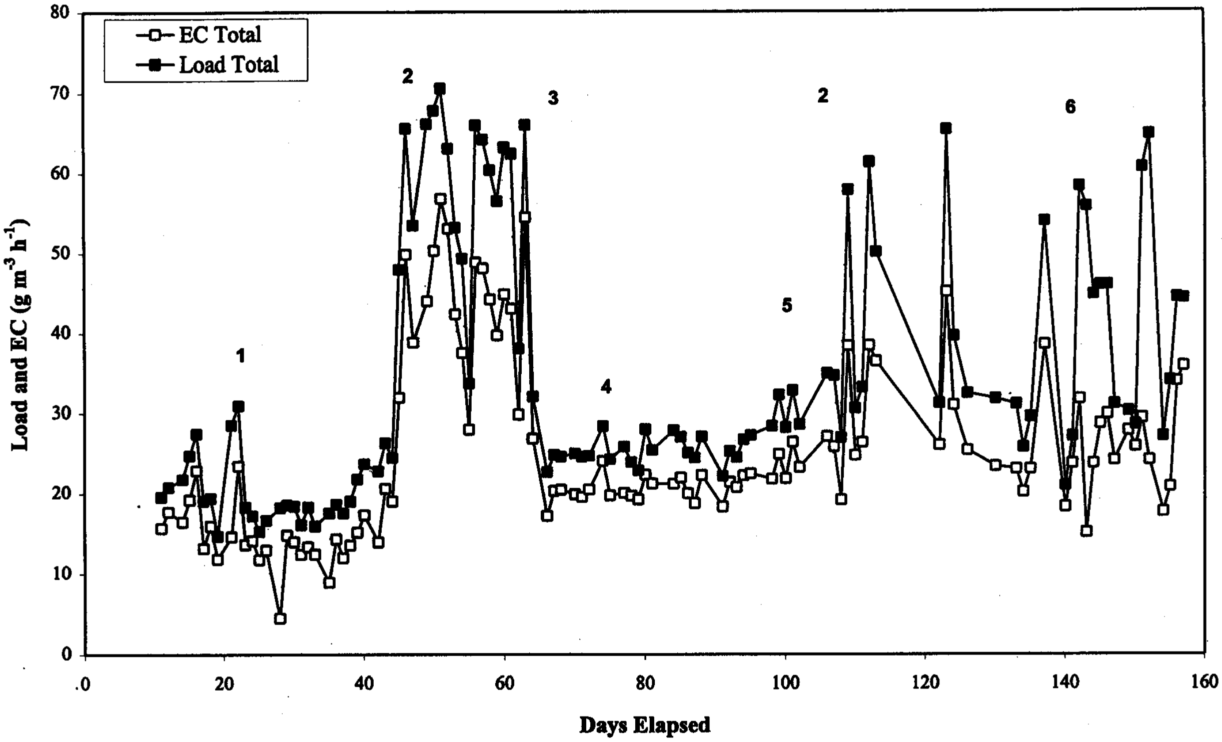

FIGURE 4. Total load and elimination capacity for biotrickling filtration system. System experiments occurred: (1) nutrient concentration in water doubled; (2) styrene load artificially increased; (3) artificial styrene load decreased; (4) heating element turned off; (5) tracer test performed; (6) microbiological substrate uptake rate study performed.

systems, a large percentage of operator time involved routine system checks and resolving system component operating problems. In general, the system required 75 hrs (6.9 h per week) of operator attention. Of this time, 55% was dedicated to routine checks and 45% to resolving component malfunctions and operating problems (Figure 3). Typically, no one component was the sole reason for every system upset. Instead, a combination of component problems and malfunctions lead to other component problems. Such findings demonstrate the need for the implementation of an effective maintenance program with weekly equipment checks [6]. Items requiring weekly checks include the air sampling system (including all waste gas delivery lines), nutrient delivery system, caustic delivery system, and knockout pod filter. Monthly checks may include inspection of the conductivity probes, pressure gauges, pH probes, and flowmeters for proper calibration and operation.

Industrial Site Specific Upsets

System upsets can also be caused by specific problems associated with a particular site. In general, upsets that occurred at the bathtub manufacturing facility were unavoidable and caused by plant personnel with little knowledge about the operation of the biotrickling filter reactor. Such problems included personnel unknowingly disconnecting the power and water supplies, as well as unexpected power surges or outages from the main plant power. Such problems are difficult to alleviate at a plant where activity is high near the reactor. Appropriate signs, warnings, and barricades (fences) may be set up near or around the reactor to prevent such problems. However, space is often limited and such preventive measures may affect plant operation.

Additional problems may be generated at an industrial plant which are specific to its operation. The generation of dusts and particulates from the plant may slowly affect the system components. Though this prototype reactor was operated for a fairly short period of time, some corrosion and wearing of the system components was evident. In general, the environment where the reactor will be placed is of great importance. The system should be in an area highly accessible to water and electricity, but not such to be a nuisance to plant personnel. Care should also be noted about the surroundings of the plant. Rodents, snakes, lizards, and spiders thrive in damp areas; they had a tendency to converge under or near the biotrickling filter reactor in this study. Such conditions may seem obvious, but are noteworthy because of their great importance to the safety of the system and operator alike.

Resolving Performance Problems

After the initial start-up phase, when continuous operation began, early system performance demonstrated sustained elimination capacities of 15 g m^{-3} h^{-1} with 70% overall removal efficiency (50% removal efficiency and 20 g m^{-3} h^{-1} across the first tank in series). After a more stable biomass was established on the packing material by artificially increasing the styrene load to the system (discussed below), elimination capacity increased to sustained levels of 24 g m^{-3} h^{-1} (35 g m^{-3} h^{-1} across the first tank in series) with 70 to 85% overall removal (Figure 4).

For biofilter technology, numerous research studies have been performed on the treatment of styrene. Sabo et al. (1993) and Arnold et al. (1997) demonstrated sustainable styrene elimination capacities of approximately 12 g m^{-3} h^{-1}. Hartmans et al. (1990) reported styrene elimination rates of 50 g m^{-3} h^{-1} but could only maintain 100% conversion at a maximum load of 15 g m^{-3} h^{-1}. Though results from this five-month biotrickling filter study were comparable or higher to those previous biofilter studies, the testing of possible system problems and operating conditions was warranted in an attempt to enhance reactor performance. Nutrient supply was increased, reactor water temperatures were decreased, and organic loading was artificially supplied during times when the plant was not operating to create more steady state like conditions (Figure 4). In addition, experiments were performed to establish if reactor performance was hindered by poor air distribution through the filter bed or by biological uptake limitations.

Environmental Conditions

Environmental conditions found in a biotrickling filter reactor require optimization in order to host a thriving microbial population. Conditions such as water temperature, nutrient concentration, pH, and conductivity affect microbial growth and metabolism.

The liquid recycle water temperature was significantly altered in an attempt to enhance removal performance. Initially, the temperature of the water passing over the filter bed was maintained between 30-34°C using a water immersion heater. The test-site location ambient conditions generally ranged from 26°C (at night) to 36°C (during hot summer days). Based on this narrow temperature range of ambient conditions, it was speculated that substantial operational cost savings could be incurred by turning off the heating element without a correlating loss in removal performance. On day 73 (Figure 4, Point 4) of the experiment, the heating element was turned off and little to no correlation was established between reactor recycle liquid temperature and removal performance. It has been suggested that such behavior is an indication of a mass transfer limitation because biological kinetics usually has greater temperature sensitivity than transfer kinetics [2]. However, in the absence of specific information on the activation energy of styrene biodegradation, such a conclusion may be too expeditious.

Another environmental condition, the nutrient concentration, was changed and the effects on performance were monitored. The nutrient concentration of the recycled water was doubled (to 1.4/1.0/1.2 g l^{-1} of N/P/K) during the course of the experiment to determine whether a nutrient limitation was occurring. Once again, no correlation of increasing nutrient content to reactor performance was established (Figure 4, Point 1). Possible nutrient limitations were also dismissed as biomass growth increased rapidly during high styrene load experiments (See Transient Operating Conditions). All other environmental conditions appeared to be suitable for microbial growth (i.e., pH, conductivity), so further investigation into possible enhancements in contaminant removal performance turned to potential problems caused by site specific operating conditions.

Transient Operating Conditions

The bathtub manufacturing facility operated in a transient state. The plant would generally operate Monday morning through Saturday morning and shut down over the weekend. During this plant downtime, liquid recycle and ambient air continued to be supplied to the biotrickling filter reactor to avoid anaerobic conditions from developing in the reactor and malodorous emissions occurring during system restart. However, no substrate (styrene) source was supplied to the microbial population. Under such starving conditions, the microbes in the system quickly reverted to endogenous respiration. Inevitably, through measurements made with the load cells, attached biomass weight in the reactors declined over the weekend. When the plant restarted operations on Monday morning and styrene was supplied to the microbes, system performance was very poor (0 to 30 % removal). The reduction in cell viability and loss of active biomass over the weekend likely contributed to the initial poor removal. In addition, because of the low solubility of styrene, an initial mass transfer limitation may have occurred once styrene was reintroduced into the reactor. After a day of plant operation passed, gradual improvement to pre-weekend performance levels was achieved. This slow recovery made it difficult to achieve rapid biofilm growth on the media bed (Figure 5). Generally, in the laboratory, it is the opposite problem. Previous research in the laboratory has demonstrated the problem of excessive biomass growth for systems where loading was high and a steady supply of contaminant existed [10, 11]. However, in the field, at low loadings and discontinuous operation, it could be a problem to achieve a stable and sufficient density of biomass.

To test the possible theory of reaction limitations in the biofilm, styrene removal was studied at higher concentrations. A metered stream of liquid styrene was directly injected into the air stream prior to entering the blower (the air flow remained constant). Combined with the load from the plant (26 g m^{-3} h^{-1} during the week), a total average load of 66 g m^{-3} h^{-1} was applied to the reactor continuously for approximately two weeks (days 44 to 60). This steady state, high load condition caused biofilm to generate rapidly on the packing material (Figure 5). Elimination capacity also improved to values of 45-50 g m^{-3} h^{-1} (55-65 g m^{-3} h^{-1} across the first tank in series). Such results possibly indicate that the actual styrene uptake kinetics in the biofilm was of a positive order and the biofilm was not saturated during normal operating conditions. Consequently, raising the substrate concentration could increase biological kinetics.

When the styrene load was reduced and transient conditions continued, performance declined (but was

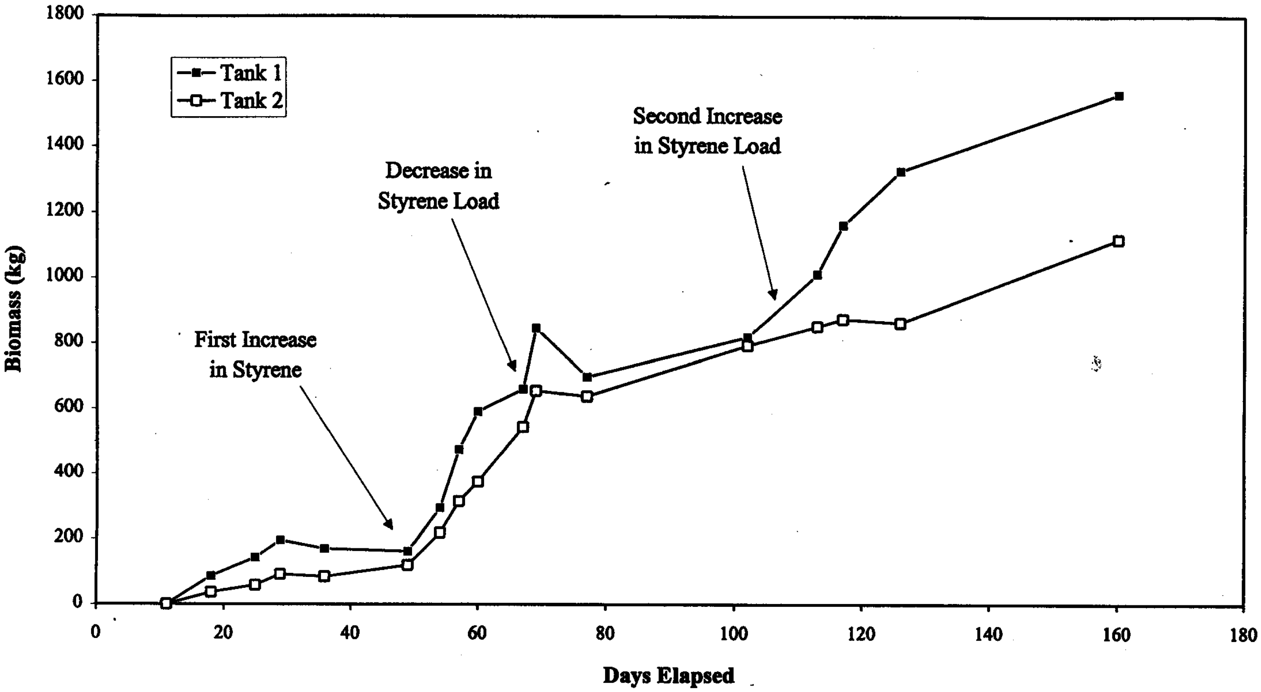

FIGURE 5. Biomass accumulation after styrene load additions to the system. Secondary load increase not discussed in paper.

still better than previous levels) to sustained levels of 20-24 g m^{-3} h^{-1} (33-35 g m^{-3} h^{-1} across the first tank in series). The increase in biomass was approximately 500 kg per tank (400% increase compared with prior levels before the increase in load), but performance only increased 25-30%. A rough estimate of the biofilm thickness based on the additional biomass formed (500 kg), assuming a packing surface area to volume ratio of 125 m^2 m^{-3}, wet biomass density of 1000 kg m^{-3}, and 100% coverage, was calculated to be 700-900 μm in thickness. Despite the large increase in biomass, the small moderate increase in elimination capacity suggests that most of the biomass that accumulated was inactive and that future research efforts should be placed in the optimization of the amount of active biomass. Cox (1995) was able to sustain 60 g m^{-3} h^{-1} of styrene removal with efficiencies greater than 80% using a packing material in a biofilter with a surface area to volume ratio of 860 m^2 m^{-3}. The Jaeger Tri-Pack® used in this study had a surface area to volume ratio of only 125 m^2 m^{-3}. This caused poorer biofilm density distribution and possibly explains the lower styrene elimination. Such a thick biofilm could have created mass transfer limitation problems or oxygen diffusion limitations, limiting performance. Even so, in the absence of more detailed information, it is difficult to conclude whether the performance could be attributed to biological reaction limitation or mass transfer limitation. The low influent concentrations and the intermittent operation encountered at the test site suggest the former, but it is possible that both types of limitation occurred at different locations in the reactor. Further investigation of possible problems with air distribution in the reactor and microbiological limitations were warranted.

Channeling of Air and Packing Material Surface Area

Though some improvement in removal was seen with the system after the biomass increased, a continued increase in removal performance was not noted. Heterogeneities in the biomass distribution possibly caused channeling of air or dead zones of activity. The packing material utilized for the filter bed had a fairly high void space (95%), but problems with air channeling were suspected and required testing. A tracer test was performed to determine if any portion of the bed was unutilized. The styrene load was completely halted and a pulse of propane was injected into the inlet pipe leading to the first tank of the system (downstream of the blower). The pulse injection experiment was repeated three times. The PLC and FID continuously monitored the air along a port on the outlet piping from tank 1. From these measurements, a retention time of the pulse was experimentally determined. The triplicate runs were averaged. Using this experimentally determined retention time and knowing the flow through the reactor, an experimental void volume was calculated to be 3.7 m^3. From the geometry of the piping, the tank, the liquid holdup (estimated), the packing material, and the biofilm present in the first filter bed, the calculated total void volume was determined to be 4.1 m^3. A dead void volume was then calculated from the difference in the calculated void volume and the experimentally determined void volume:

(1) Dead Volume = (Inlet Pipe Volume + Tank 1 Volume + Outlet Pipe Volume - Bare Packing Volume - Biomass Volume - Dynamic Hold-up Volume) - (Experimentally Determined Residence Time of Tracer x Air Flow Rate)

The dead void volume was 0.4 m^3, roughly 10 % of the filter bed. This amount of dead void volume is moderately significant, but it does not constitute a major portion of the bed. Hence, limited styrene removal could not be attributed solely to channeling of air. Such pulse tests provide a quick and easy assessment of bed usage (and performance), and should be performed with all pilot- and full-scale reactors at least twice a year.

Biological Limitations

The final phase of the experiment investigated possible biological limitations with the microbial populations. Specific oxygen uptake rates were determined for cells immobilized in the biofilm by adding styrene to a suspended biofilm sample. Using an oxygen probe in a respirometry flask (YSI, Yellow Springs, CO), depletions in oxygen were measured as the substrate was consumed. In addition, controls were set up to establish the amount of endogenous respiration that occurred without styrene addition. Knowing the oxygen consumption based on the styrene degradation and correcting for oxygen consumption from endogenous respiration, the amount of oxygen consumed per mass of dry biomass per time was calculated. Maximum uptake rates were calculated to be 0.2 µg of oxygen mg^{-1} dry biomass min^{-1}. Such uptake rates are 3 to 10 times lower than uptake rates measured for the styrene-degrading fungus *Exophiala jeanselmei* used in a biofilter experiment treating styrene gases [5]. By isolating pure cultures through streak plating and inoculating Biolog® GN Identification Plates (Biolog, Hayward, CA), the dominant fixed-film microbes performing the degradation in the reactor were tentatively identified as *Pseudomonas diminuta* and *Pseudomonas mendocina*. Though difficult to correlate batch-scale experiments in the laboratory with actual pilot-scale results, such uptake measurements provide another possible explanation as to why contaminant removal in the biotrickling filter was limited. These particular *Pseudomonas* sp. may not have had the constitutive enzymes, or proficient inductive enzymes, necessary for effective styrene treatment, or the enzyme turnover may have been too low. Contrary to compost biofilters, where a large indigenous population is present on the medium at the start and where inoculation is often needless, biotrickling filters do need an efficient inoculation to establish a thriving process culture. Such experimental results indicate a possible weakness with inoculating a biotrickling filter with activated sludge and then assuming a suitable degrading population will develop. Instead, these findings magnify the importance of inoculating a biotrickling filter reactor that is treating a pure stream of styrene with highly proficient styrene degrading microbes.

CONCLUSIONS

The use of a biotrickling filter reactor in an industrial setting posed many additional challenges not seen at the bench-scale level in the laboratory. Both operational and performance problems unique to the particular reactor design and its site location constantly surfaced. Operational problems included the malfunction of water pumps, poor performance of water level sensing equipment, sampling system malfunctions, and plant power outages. Some problems were quickly alleviated, while others were more difficult to control and caused repetitive system upsets. Throughout the experiment, the need for more reliable, advanced equipment (float sensors, nutrient pumps, etc.) was evident. More advanced equipment requires higher capital costs. In some instances, these higher costs are warranted to prevent frequent system upsets that contribute negatively to reactor performance. In designing this type of system, a balance exists between the capital and the operational costs needed to maintain the system so that upsets are minimal.

The biotrickling filter reactor performed well and provided a sustained styrene elimination capacity of up to 24 g m^{-3} h^{-1} (35 g m^{-3} h^{-1} across the first tank in series) with 70 to 85 % removal. Possible performance problems were assessed to enhance the system's overall pollutant removal capacity. The surface area to volume ratio of the packing may have limited the effective biofilm density in the system. This created large quantities of inactive biomass and possibly led to some mass transfer limitation. Minimal effect on pollutant removal was demonstrated when the environmental conditions of water temperature and nutrient concentration were varied inside the reactor. Transient operation of the plant made it difficult to establish an effective, active biofilm on the packing material. This fact alone contradicts many results from research efforts of continuous, steady state systems operated in the laboratory, for which biomass overgrowth is a common problem. Therefore, additional work is needed in the laboratory to assess the varying effects of transient operation of biotrickling filter reactors. Focussing on the design, possible problems of air channeling were dismissed by results of a propane tracer study that determined more than 90% of the bed of the first tank in series was effectively being utilized. Microbial limitations were investigated and preliminary results described a microbial consortium of styrene degraders, dominated by *Pseudomonas* sp., with low maximum substrate uptake rates compared with other laboratory research results of pure styrene-degrading cultures. Such a problem points to the need for better defined inoculation procedures of biotrickling filtration reactors.

ACKNOWLEDGEMENTS

The University of California Toxics Substance Research and Teaching Program provided major funding for this project. Additional support came through LASCO Bathware, Inc. (Anaheim, CA) and the South Coast Air Quality Management District (SCAQMD). Special thanks to Isidro Pe and Pete Dennis of LASCO Bathware, Inc. for their assistance in implementing the technology at their site. Additional thanks to Larry Watkins and Mohan Balagopalan of the SCAQMD for their assistance in permitting the reactor and to Jaeger Products (Houston, TX) for their donation of the filter bed packing material.

LITERATURE CITED

1. Arnold, M., Reittu, A., von Wright, A., Martikainen, and P. J., Suihko, M.L., "Bacterial degradation of styrene in waste gases using a peat

filter," Appl. Microbiol. Biotechnol.,48, pp. 738-744 (1997).

2. Barton, J.W., Klasson, T., and Davison, B.H., "Extended operation and control of biomass overgrowth in biofilters designed for VOC removal," Proceedings of the 1997 Annual Meeting of the Air & Waste Management Association, Toronto, Canada (June 1997).
3. Cox, H.H.J., "Styrene removal from waste gas by the fungus Exophiala jeanselmei in a biofilter," Ph.D Thesis, University of Groningen, The Netherlands (1995).
4. Cox, H.H.J., and Deshusses, M.A., "Biological waste air treatment in biotrickling filters," Current Opinion in Biotechnology, 9(3), (June 1998).
5. Cox, H.H.J., Moerman, R.E., van Baalen, S., van Heiningen, N.M., Doddema, J., Harder, W., "Performance of a styrene-degrading biofilter containing the yeast Exophiala jeanselmei," Biotechnology and Bioengineering, 53(3), pp. 259-266 (February 1997).
6. Devinny, J.S., Deshusses, M.A., and Webster, T.S., Biofiltration for Air Pollution Contr ol, First Edition. CRC Press, Inc., Boca Raton, FL, (September 1998).
7. Hartmans, S., Tramper, J., and de Bont, J.A.M., "Biological waste air treatment," Proceedings of the Fifth European Congress on Biotechnology, 2, pp. 659-662 (1990).
8. Holubar, P, Andorfer, C., and Braun, R., "Prevention of clogging in trickling filters for purification of hydrocarbon-contaminated waste air," Proceedings of the 1995 Conference on Biofiltration, eds. Hodge, D. and Reynolds, F. E. Jr., Los Angeles, California (October 1995).
9. Sabo, F., Fisher, K., and Baumeister, R., VDI Berichte NR 1034, pp. 521-539 (1993).
10. Sorial, G., Smith, F.L., Suidan, S.T., Biswas, P., "Evaluation of trickle bed biofilter media for toluene removal," J. Air & Waste Management Association, 45, pp. 801-810 (October 1995).
11. Togna, A.P., and Folsom, B., "Removal of styrene from air using bench-scale biofilter and biotrickling filter reactors," Proceedings of the 85th Annual Meeting & Exhibition of the Air & Waste Management Association, Kansas City, MO, (June 1992).
12. Weber, F.J., and Hartmans, S., "Toluene degradation in a trickle bed reactor- Prevention of clogging," VDI-Berichte NR 1104, pp. 161-168 (1994).
13. Webster, T.S., Togna, A.P., Yang, Y., and Guarini, W. J., "From bench- to pilot-scale experimentation: The Treatment of volatile organic compound emissions from spray paint booth applications using a biological trickling filtration reactor," Proceedings of the 1998 Annual Meeting & Exhibition of the Air & Waste Management Association, San Diego, California, (June 1998).
14. Zuber, L., Dunn, I.J., and Deshusses, M.A., "Comparative scale-up and cost estimation of a biological trickling filter and an air lift reactor for the removal of methylene chloride from polluted air," J. Air & Waste Management Association, 47, pp. 969-975 (1997).