BIOTECHNOLOGY AND BIOENGINEERING
Chinese Journal of Chemical Engineering, **18**(1) 113—121 (2010)

Treatment of Benzene, Toluene and Xylene Contaminated Air in a Bioactive Foam Emulsion Reactor

Farshid Ghorbani Shahna[1,2], Faride Golbabaei[1,*], Javad Hamedi[3], Hossein Mahjub[4], Hossein Reza Darabi[5] and Seyed Jamaladdin Shahtaheri[1]
[1] Department of Occupational Health, School of Public Health & Institute of Public Health Research, Tehran, Iran
[2] Department of Occupational Health, School of Public Health, Centre of Health Research, Hamadan University of Medical Science, Hamadan, Iran
[3] Division of Microbiology, Department of Biology, Faculty of Science, University of Tehran, Iran
[4] Department of Biostatics & Epidemiology, School of Public Health, Centre of Health Research, Hamadan University of Medical Science, Hamadan, Iran
[5] Chemistry & Chemical Engineering Institute of Iran, Tehran, Iran

Abstract A novel bioactive foam emulsion bioreactor for benzene, toluene and xylene (BTX) contaminated air streams treatment has been developed. The gas-liquid interfacial area by biocompatible foam and driving force for mass transfer by a water immiscible organic phase were increased in this reactor. The effect of several parameters such as gas residence time, oxygen content, and organic phase concentration on bioreactor performance was studied. Experimental results showed an average elimination capacity (EC) of 220 $g \cdot m^{-3} \cdot h^{-1}$ with removal efficiency (RE) of 89.59% for BTX inlet concentration of 1 $g \cdot m^{-3}$ at 15 s gas residence time in the bioreactor. The statistical developed model predicted that the maximum elimination capacity of the reactor for BTX could be reached to 423.45 $g \cdot m^{-3} \cdot h^{-1}$. Continues operation of the bioreactor with high EC and RE was demonstrated by optimizing the operational parameters of the bioreactor. Overall the results suggest that the bioreactor developed can be very effective systems to treat BTX vapors.
Keywords air pollution control, bioactive foamed reactor, biodegradation, BTX

1 INTRODUCTION

Volatile organic compounds (VOCs) are one of the important groups of air pollutants. These compounds are often found in emission of several sources such as refiners, petrochemical units, chemical plants, storage tanks and vehicle exhausts [1, 2].

Because of their relatively high vapor pressure, they readily volatilize to atmosphere and thus distributed over large regions. The emission of VOCs in the atmosphere, causing different environmental problems such as ground level ozone formation, stratospheric ozone depletion, photo chemical reactions and global green house effect [2, 3].

Among of VOCs, simple aromatic benzene, toluene and xylene (BTX) are toxic substances that classified as priority pollutants by the U.S environmental protection agency [4]. Releasing BTX into the ambient air may lead to adverse effects on public health and welfare [5].

Several physical and chemical gas cleaning techniques such as adsorption, incineration, absorption, thermal and catalytic oxidation have been developed to treat BTX, but the costs for chemical and energy consumption as well as further treatment or disposal of secondary wastes are two major disadvantages of these techniques [6–8].

Biological treatment is an established technology for air pollution control that can be an attractive alternative to chemical and physical techniques for a cost-effective and environmentally safe method [6, 9, 10]. Biofilter and biotrickling filter are the most widely used bioreactors, however, both of them have essentially restrictions [11–13]. Due to the limited cell activity of essentially resting cells in the reactors, biofilters typically have low pollutant elimination capacity. The biotrickling filters often exhibit higher performance than biofilters, but it can be clogged from excess biomass growth on the bed, which results in high pressure drop and process instability [14–16].

Due to these limitations, the classic bioreactors are not considered as appropriate control techniques for treating high concentration pollutants.

For overcoming these inherent problems, two techniques have been introduced in recent years including (I) two phase partitioning bioreactor (TPPB), which is based on the use of water based immiscible and biocompatible organic solvent that is allowed to float on the surface of a cell containing aqueous phase [9, 16–18]; and (II) foamed emulsion bioreactor (FEBR) that consists of an emulsion of highly active pollutant-degrading microorganisms and a water-immiscible organic phase, which is made into a foam with the air being treated [9, 11, 19]. The FEBR is similar to TPPB, but the amount of organic phase is low and it uses a biocompatible surfactant for foam production. To attain high volumetric pollutant removal rates, the FEBR relies on a high-density culture of actively growing organisms. At the same time, bed clogging and associated pressure drop problems are avoided by using moving foam rather than an immobilized culture growing on a bed [11].

Received 2009-02-16, accepted 2009-06-04.
* To whom correspondence should be addressed. E-mail: fgolbabaei@tums.ac.ir; fgolbabaei@yahoo.com

Another alternative is a bioactive foam reactor (BFR) operated with a surfactant bubble solution containing pollutant degrading microorganisms [20]. In this reactor, organic phase has not been used. The previous studies demonstrate that organic phase has a key role in absorption of VOCs, especially at high concentrations. In comparison to biofilter and biotrickling filter, BFR has a higher elimination capacity (EC) for large interfacial area between the gas and fine foam. The removal efficiency (RE) in BFR is reduced at the high concentration (generally higher than 300 $mg \cdot m^{-3}$) [12].

Toluene as representative of VOCs has been investigated in recent studies but the behavior of BFR for biodegrading mixture of BTX has not been studied. The purposes of this study were (I) design of the two phase foam bioreactor for biodegrading of BTX mixture air laden stream and study of organic phases, surfactants and variables for achieving optimum operation conditions for BTX removal; (II) determination of the Maximum EC, RE and optimum values of organic phase, oxygen content, mode of operation, residence time and associated parameters; (III) study of the bioreactor behavior on change of operational variables; and (IV) monitor of bioreactor behavior for continuous operation mode.

2 MATERIALS AND METHODS

2.1 Microorganisms and media

The soil of oil and petrol storage tanks area at a storage and Distribution Company was sampled based on the assumption that it contains BTX degrading microorganisms. The sampled soil was scrubbed with sterile NaCl serum at the sterile condition and the produced dark solution was poured in a glass vial. After 6 h the clear supernatant of samples was poured in the 1 L flask and mineral nutrient added to it with 3∶1 (volume) ratio. The nutrient medium consisted of 1.2 $g \cdot L^{-1}$ KH_2PO_4, 1.2 $g \cdot L^{-1}$ K_2HPO_4, 0.2 $g \cdot L^{-1}$ $MgSO_4$, 1 $g \cdot L^{-1}$ NaCl, 1 $g \cdot L^{-1}$ KNO_3 and trace element that comprised to 26 $mg \cdot L^{-1}$ $CaCl_2 \cdot 2H_2O$, 5.5 $mg \cdot L^{-1}$ EDTA $Na_4(H_2O)_2$, 1.3 $mg \cdot L^{-1}$ $FeCl_3 \cdot 4H_2O$, 0.12 $mg \cdot L^{-1}$ $CoCl_2 \cdot 6H_2O$, 0.1 $g \cdot L^{-1}$ $MnCl_2 \cdot 2H_2O$, 0.07 $mg \cdot L^{-1}$ $ZnCl_2$, 0.06 $mg \cdot L^{-1}$ H_3BO_3, 0.025 $mg \cdot L^{-1}$ $NiCl_2 \cdot 6H_2O$, 0.025 $mg \cdot L^{-1}$ $NaMoO_4 \cdot 2H_2O$, and 0.015 $mg \cdot L^{-1}$ $CuCl_2 \cdot 2H_2O$.

The BTX-degraded microorganisms were extracted and enriched in two steps. First, 60 ml of the above mentioned solution was poured into a 300 ml bottle fitted with a butyl rubber septum. The remained 240 ml of the bottle headspace guaranteed sufficient air for aerobic degradation. As the sole carbon and energy source, 100 $mg \cdot L^{-1}$ of BTX was added to any bottle. All flasks were incubated at 25−30ºC temperature on a rotary shaker at 150 $r \cdot min^{-1}$ in a dark environment. The ability of samples for degrading the BTX in headspace and solution was evaluated by gas chromatography (UNICAM 4600, United Kingdom) equipped with flame ionizing detector (FID). A similar flask containing 1% of NaCN as a microbial respiration BTX loss from volatilization and diffusion from septum was prepared. After consumption of BTX, samples washed with sterile air and the cycle was restarted. In the further cycles, concentration of injected BTX into bottles was increased to 200, 300 and 400 $mg \cdot L^{-1}$. In each cycles, dissolved oxygen (DO) was measured with HACH DO meter (model sesion6, USA). Optical density as an index of biomass growth was monitored with UV-VIS spectrophotometer (UV-1700 Shimadzu Pharmaspec, Japan) at 600 nm. After several cycles, the enriched centrifuged solution and fresh nutrient mineral solution was mixed. In the second step, the mixed culture was grown by bubbling 0.8−1.2 $g \cdot m^{-3}$ BTX-laden air through nutrient medium in a 3L flask and concentrated by centrifugation before injecting to the bioreactor.

The biomass concentration of this culture medium was measured by overnight drying of aliquots at 70ºC. The minimum concentration of biomass for introducing to the bioreactor was 8 $mg \cdot L^{-1}$.

2.2 Bioreactor setup and operation

The bioreactor consists of an air compressor, an oxygen tank, dehumidifier, activated carbon beds, dynamic system for generation of BTX vapors, foam column, cell reservoir, defoamer and controlling devices (Fig. 1). The compressed air after dehumidification and oil mist removing in the bed packed with ceramic enters to activated carbon bed for elimination of VOCs and other organic pollutants. Then, dry and clean air was mixed with pure oxygen. This bioreactor had high oxygen and pollutant mass transfer rates due to large interfacial area between gas and liquid of fine foam and a high portioning of pollutants into the organic phase [9, 11]. Thus, for achieving a high elimination capacity and removal efficiency of pollutants, especially at the concentration of >0.5 $g \cdot m^{-3}$ BTX, the oxygen in air was insufficient and needs additive oxygen. After mixing of air and oxygen, it is introduced to dynamic generation system of BTX air stream. Introduced air first is divided to three parts that each part needs for vapor generation (B, T and X). Then, each part of air was subdivided to two sections. A slow stream of air was bubbled through impinger (glass vial) containing pure solvent (GC grade, Merck Co, Germany) and the second stream was bypassed. After that, two streams are mixed together again. With adjusting of flow rate of two streams, the various concentrations for B, T and X were achievable. The three vapor born streams were mixed again and the outlet stream of dynamic vapor generator system contains specific concentration of BTX. The BTX contaminated air streams was metered with flow meter and introduced to foam column. It should be stable of the volume of benzene, toluene and xylene in their impingers and temperature for the period of study to maintains constant generation of BTX vapors concentration. To remove the air born microorganisms, the contaminated air to BTX was passed through a sterile

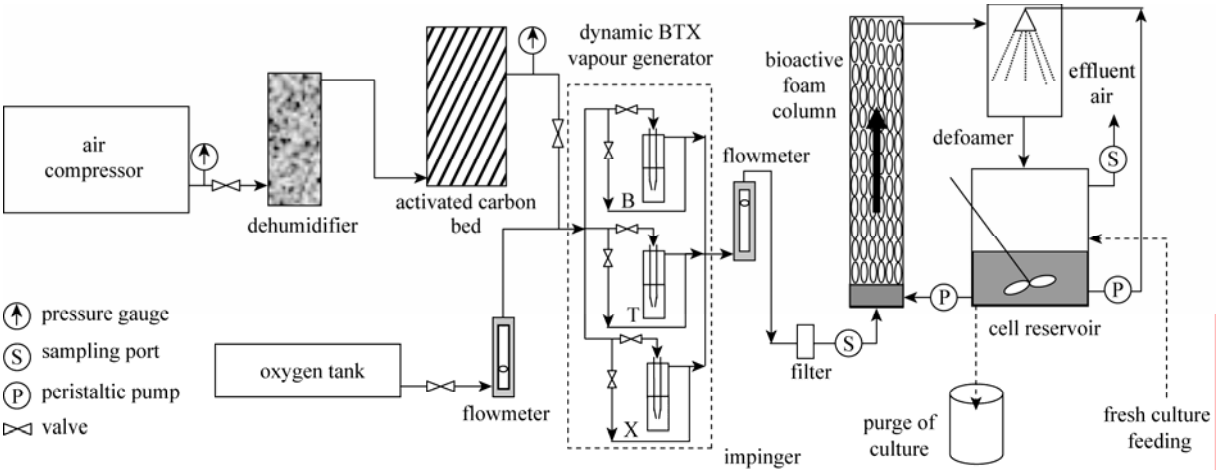


Figure 1 Schematic of the studied bioactive foamed emulsion reactor

bacteriological filter (0.22 μm pore size). For all of the experiments described herein, the heat resistant parts of bioreactor autoclaved and thus ethanol vapor has been rinsed up to bioreactor for several hours for sterilization of unresisting parts.

The BTX contaminated air stream enters to foam column. The Plexiglas foam column (4 cm diameter, 48 cm high and 0.6 L volume) had a fine air sparger at the bottom of column. The introduced BTX contaminated air stream passed through the sparger, while emulsion was injected at the bottom of bioreactor by a peristaltic pump (SR25-S300 Thomas Co, USA). The injected emulsion consists of nutrient medium, the active culture, the *n*-hexadecane 5% (by volume) as organic phase (Merck Co) and 0.2% (by volume) Triton X-100 as biocompatible surfactant (Merck Co).

Fine foams were generated and rinsed up the column by passing of air streams through the emulsion. Temperature of room and bioreactor has been constant at 30°C on experiment period for homogenous foam production and microorganism activity. After rinsing the reactor, the foams left the column through a side port and were defoamed in a defoamer with continuous spraying the emulsion from cell reservoir. The defoamer was a 1 L volume glass flask. The sprayed and defoamed liquid was returned to reservoir (a 1 L flask) and recycled to foam column. The liquid in cell reservoir was continuously stirred to be introduced to column as a homogenous emulsion. Total volume of emulsion in the bioreactor was 0.6 L. Two ports placed before foam column and after cell reservoir at outlet of bioreactor for direct sampling of air stream.

The continuous operation strategy with changing of 10%−20% (by volume) of emulsion within 24 h with similar fresh emulsion, except the fourth amount of nitrogen source (4 $g \cdot L^{-1}$ KNO_3) in fresh, was selected to supply adequate nutrient for cells. The fresh culture had the similar percent of organic phase (5% *n*-hexadecane) and surfactant (0.2% Triton X-100).

The effects of organic phase amount, oxygen content at introduced gas streams and residence time (or linear velocity) of gas in bioreactor on the RE and EC of BTX (individual and total) were determined for various conditions. For selection of the best organic phase at optimum amount, *n*-hexadecane, oleic alcohol and 1-octadecene were studied at 0−7%. The effectiveness of these compounds for BTX absorption was demonstrated (16). The effect of oxygen content at introduced gas stream on the RE and EC was experimented by introducing gas streams containing 20% to 60% oxygen. This effect was studied for concentration of 75 to 1800 $mg \cdot m^{-3}$ of BTX (contain of 25 to 600 $mg \cdot m^{-3}$ for each pollutants). Indeed, the bioreactor response for residence times of 15 s to 60 s (0.48 to 1.92 $m \cdot min^{-1}$ linear velocity) was investigated. For determining the RE and EC in the previously mentioned conditions, the experiments were repeated for three times and the average was reported. In the next step, the RE and EC were measured for BTX inlet concentration of 100 to 1800 $mg \cdot m^{-3}$ at optimum conditions. Finally, the performance of the bioreactor at the continuous operation mode was monitored for one week.

2.3 Analytical methods

To determine removal efficiency and elimination capacity of the bioreactor, the gaseous samples were collected from the two sampling port placed before foam column and after cell reservoir at the outlet of bioreactor by gastight syringe. Samples were directly injected into gas chromatograph (UNICAM 4600, United Kingdom) equipped with flame ionizing detector (FID) and glass column (1.5 m×4 mm id) packed with 10% SE 30 on chromosorb W-AW-DMCS 100−120. The concentration of BTX was calculated with comparison of produced peak area against standard curve.

The concentration of CO_2 at inlet and outlet of bioreactor were measured with Testo model 535 CO_2 meter (Hotek technologies Inc, USA). The carbon content of CO_2 was calculated by determining the differences of inlet and outlet concentration of CO_2. The

percent of C-mineralized was determined with dividing C-CO_2 to carbon content of BTX biodegraded (C-CO_2/C-BTX biodegraded). The dissolved oxygen of nutrient culture was monitored continuously by HACH DO meter (model sesion6, USA).

To measure BTX concentration in liquid phase, 30−50 ml of purge culture was filtered by the sterile bacteriological filter to remove the particulates and microorganisms. To separate of organic and aliquots phases, the filtered liquid was centrifuged at 3500 r·min^{-1} for 10 min. 10 μl of organic phase was immediately injected to GC/FID and concentration of BTX was calculated based on comparison of produced peak area against standard curve. Standard curves of GC for aliquots and gaseous phases were produced by preparation and injection of samples with standard concentrations.

3 RESULTS AND DISCUSSION

3.1 BTX degraded microorganism

The microbiological experiments were showed that the main kind of involved microorganism for BTX degradation was Alcaligenes (Achromobacter) xylosoxidas.

3.2 Optimization of surfactant and organic phase

The Triton X-100 was selected as surfactant. This surfactant is biocompatible and has a good foaming ability [12, 21]. The effect of three studied organic phase at the range of 0 to 7% (by volume) on RE and EC of reactor is shown in Fig. 2. The results illustrated that there was no significant difference among the performances of three compounds, but the *n*-hexadecane was slightly better than the others and thus selected as organic phase. *n*-Hexadecane is a biocompatible compound and has a high partition coefficient for BTX. The optimum concentration of organic phase was determined based on RE and EC of bioreactor. Results demonstrates that RE and EC of bioreactor increased relatively fast with increasing organic phase concentration up 4%. From 4% to 5% (by volume) for toluene and xylene and from 4% to 6% (by volume) for benzene, the increase of RE and EC was slow. RE and EC was remained stable with organic phase concentration of 5% to 6% (by volume). As long as the organic phase content was higher than 7% (by volume), because the oily state of *n*-hexadecane, the foam at column was slope and broken down, and thus, it was impossible to use higher organic phase concentration. Based on above founding, the selected concentration of *n*-hexadecane at aliquots was 5%. The maximum EC of 230 mg·m^{-3}·h^{-1} was achieved at RE of 95.77% for *n*-hexadecane concentration of 7% (by volume). Without organic phase the RE was reduced to 67.14% and the EC to 162 g·m^{-3}·h^{-1}. According to the principle of TPPB [16], more reduction was achieved for high concentration of BTX.

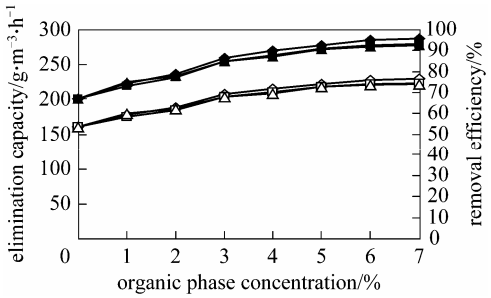


Figure 2 Effect of various organic phase concentration on the bioreactor elimination capacity and removal efficiency for BTX

(Experimental conditions: 1 g·m^{-3} of inlet benzene concentration, 15 s of residence time, 10 g·L^{-1} of biomass concentration, 2.4 L·min^{-1} of air flow rate, temperature of 30°C, 50 ml·min^{-1} of liquid flow rate and 40% oxygen content at inlet gas stream)
EC: ◇ *n*-hexadecane; □ oleic alcohol; △ 1-octadecane
RE: ◆ *n*-hexadecane; ■ oleic alcohol; ▲ 1-octadecane

3.3 Effect of oxygen concentration on the bioreactor performance

It is necessary to have high oxygen diffusion from gas phase to aliquots due to large interfacial area between gas and fine foams [9, 11]. A high biomass concentration at aliquots also needs to high oxygen for the best biodegradation of portioned pollutants into the organic phase. Based on stoichiometric calculations for complete biodegradation of BTX, especially at high concentration, the oxygen content in the compressed air was insufficient and needed to be increased. This restriction was further for inlet BTX concentration of more than 150 g·m^{-3}·h^{-1}. The additional oxygen can be supplied by using of an oxidant agent like hydrogen peroxide. But this agent may be toxicant for microorganisms. Adding the pure oxygen to bioreactor introduced gas stream was the second resolving method. The relation of oxygen content at inlet gas stream to bioreactor with EC at various inlet loads of pollutants is shown in Fig. 3. The oxygen concentration has not significant effect on EC for inlet loads below 50 g·m^{-3}·h^{-1} and 150 g·m^{-3}·h^{-1} for individual pollutants and total BTX, respectively. By increasing the inlet load to higher than 150 g·m^{-3}·h^{-1}, 20% oxygen in the air for higher elimination capacity was insufficient. In comparison to 20% oxygen for 150 g·m^{-3}·h^{-1} of inlet load of each pollutants (450 g·m^{-3}·h^{-1} for total BTX), the EC at 60% oxygen is 1.63, 1.69, 1.64 and 1.65 times for B, T, X and BTX, respectively. Note that the biomass concentration in nutrient media can affect this relation so that the needed oxygen for biodegradation should be increased with increasing biomass. However, our experiments showed that RE and EC of reactor did not change significantly for culture density higher than 10−15 g·L^{-1}. High biomass concentration produced another problem, *i.e.*, high biomass density reduced the foam stability and foam exploded sooner. It was demonstrated that the biomass concentration of 5−15 g·L^{-1} was appropriate for continuous operation of bioreactor and for this range the oxygen amount of

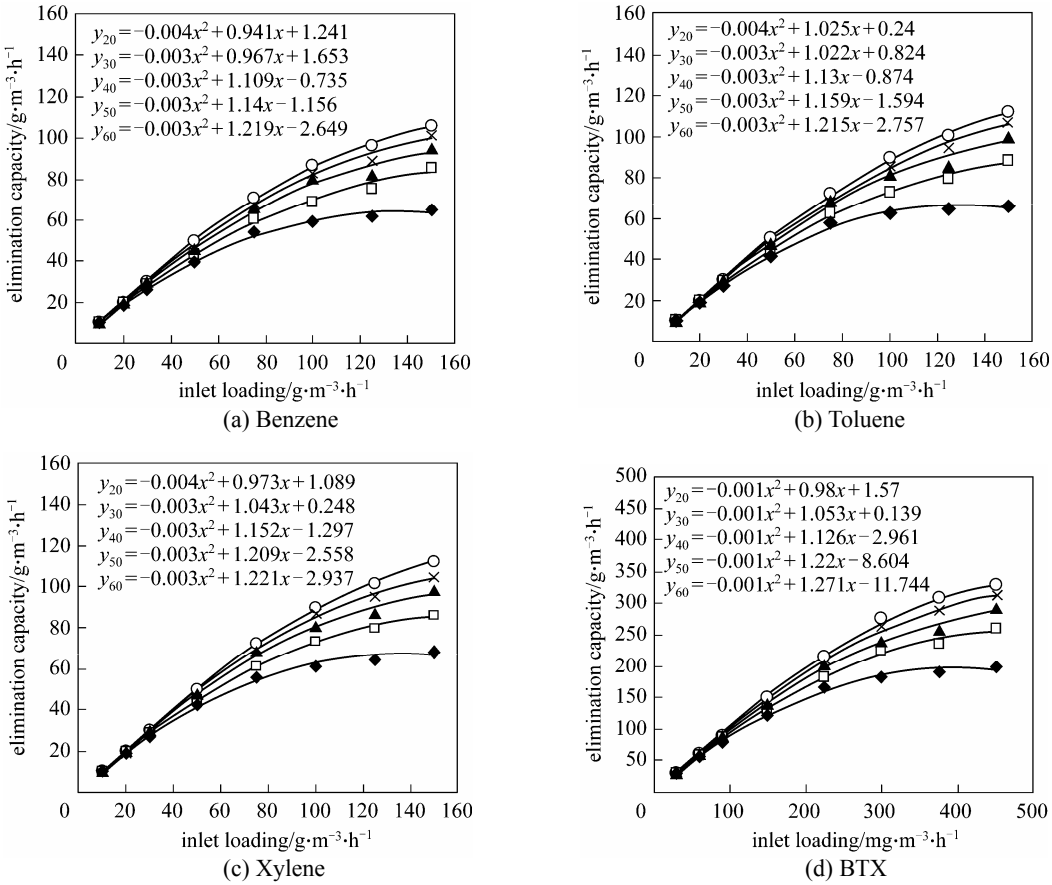


Figure 3 Effect of oxygen content of inlet air to bioreactor on the elimination capacity of benzene, toluene, xylene and BTX
(Experimental conditions: 1 g·m^{-3} of inlet BTX concentration, 15 s of residence time, 10 g·L^{-1} of biomass concentration)
◆ 20%; □ 30%; ▲ 40%; × 50%; ○ 60%

40% at inlet gas stream with BTX concentration of 1 g·m^{-3} was suitable. With 20%−21% oxygen in air 80% of BTX inlet load below 150 g·m^{-3}·h^{-1} was biodegraded, while this efficiency was decreased to 44% for the inlet load of 450 g·m^{-3}·h^{-1}. The statistical analysis showed that there is a significant relation between EC to oxygen percentage and inlet load ($R^2 = 0.91$). Based on predicted statistical model, the EC of bioreactor at pure oxygen injection condition was increased to 423.45 g·m^{-3}·h^{-1} for the inlet load of 450 g·m^{-3}·h^{-1}. High concentration of oxygen at inlet gas streams increases the operational costs of systems, thus, 40% oxygen was selected for low cost and relatively high attained EC for continuous operation of bioreactor.

3.4 Effect of gas residence time on the bioreactor performance

The effect of gas residence time (or linear velocity) on elimination capacity was studied for several inlet concentration of pollutants (Fig. 4). At residence time less than 10 s, the foam was instable and could not rinse up the column. In the range of 10−15 s, the RE of bioreactor was increased significantly but the foams were not stable completely. In the range of 15 to 60 s, the foams rinse up through column. In this range, RE was high enough for residence times of 30, 45 and 60 s for all experimented inlet loads. Moreover the RE of reactor for the 15 s was considerable (88.83%) for inlet concentration of 1050 mg·m^{-3}·h^{-1} BTX (350 mg·m^{-3}·h^{-1} for any of B, T and X). The RE and EC were decreased for inlet loads above 1050 mg·m^{-3}·h^{-1} significantly as the RE was decreased to 60.35% for inlet concentration of 1800 mg·m^{-3}·h^{-1}. With respect to results, residence time of 15 s for inlet concentration of 1−1.1 g·m^{-3} was detected as the optimum condition for operation of bioreactor.

3.5 Comparison of pollutant removal efficiency and elimination capacity for pollutants

Figure 5 shows the individual removal efficiency for each pollutant at different inlet concentration range from 20 to 600 mg·m^{-3}. It was found that the RE was 100% for all of pollutants at inlet concentration of 20 to 100 mg·m^{-3}·h^{-1}. With increasing the inlet concentration above 100 mg·m^{-3}, RE was decreased to 59.05%, 62.17% and 59.84% for benzene, toluene and xylene, respectively. The RE of toluene was the highest

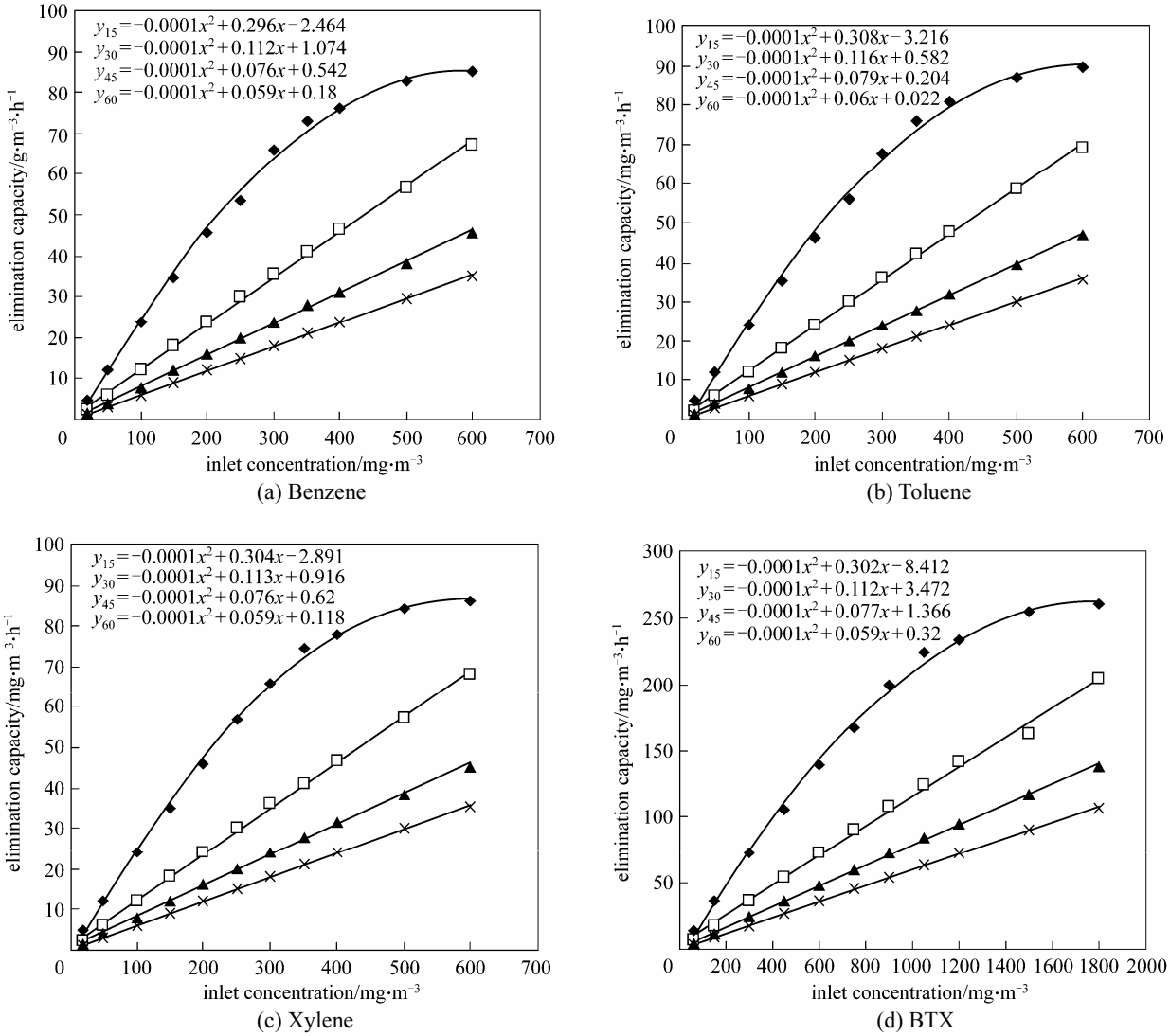


Figure 4 Effect of gas residence time on the elimination capacity for benzene, toluene, xylene and BTX
(Experimental conditions: 10 g·L^{-1} of biomass concentration and 40% oxygen content at inlet gas stream)
◆ 15 s; □ 30 s; ▲ 45 s; × 60 s

and followed by xylene and finally benzene due to the higher availability of toluene in aliquots phase. The same trend of BTX biodegradation was shown in several studies [3, 22, 23].

The EC at several inlet loads from 4.8 to 144 g·m^{-3}·h^{-1} for individual pollutants is illustrated at Fig. 6. The results showed that for inlet loads from 4.8 to 24 g·m^{-3}·h^{-1}, all of introduced pollutants to bioreactor were degraded. From 36 to 144 g·m^{-3}·h^{-1}, biodegrading was incomplete so for the inlet load of 144 g·m^{-3}·h^{-1} the EC were decreased to 85.2, 89.52 and 86.17 g·m^{-3}·h^{-1} for benzene, toluene and xylene, respectively. This can be due to restricted capacity of microorganisms for biodegradation of introduced compound. These findings were accorded to other studies [22, 23].

The EC for each of these compounds alone was higher and reached to three times of the pollutants introduced to bioreactor together.

3.6 Continuous operation of bioreactor

The performance of bioreactor was monitored for continuous operation through one week (Fig. 7). BTX inlet concentration was about 0.98−1.6 g·m^{-3}. Removal efficiency in preliminary hours was relatively low (about 80%) due to acclimation phase. After 12 h, the removal efficiency increased to 87%. The average of RE and EC for continuous operation of bioreactor during the period after 12 h acclimation phase was 89.59% and 220 g·m^{-3}·h^{-1}, respectively. In comparison to biofilter and biotrickling filter, the EC of this bioreactor for BTX was further. Based on the predicted statistical model, the maximum EC of this bioreactor can reach to 423 g·m^{-3}· h^{-1}. The maximum EC of a porous peat moss biofilter by Choi and Oh for BTX [6], compost biofilter by Torkian *et al*. for toluene and xylene [7], peat biofilter by Oh and Choi for

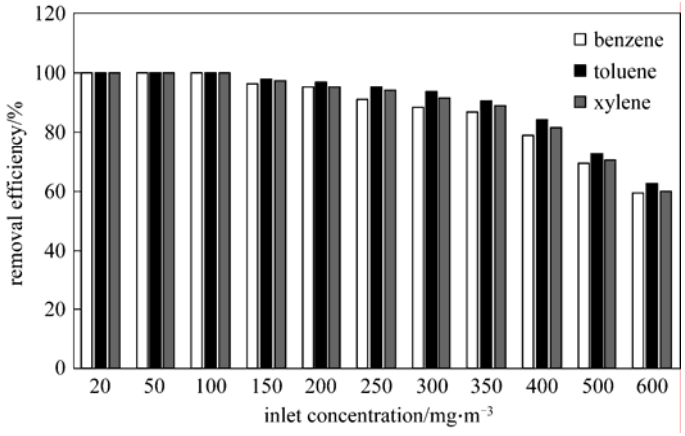


Figure 5 Removal efficiency of individual B, T, X compound for various inlet concentrations

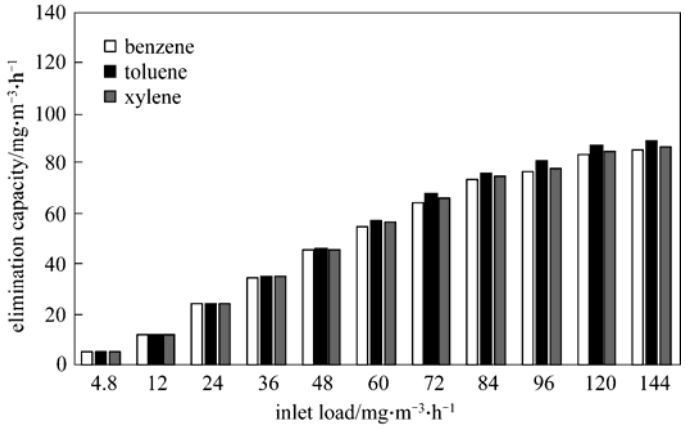


Figure 6 Elimination capacity of bioreactor for individual BTX *versus* different inlet loads

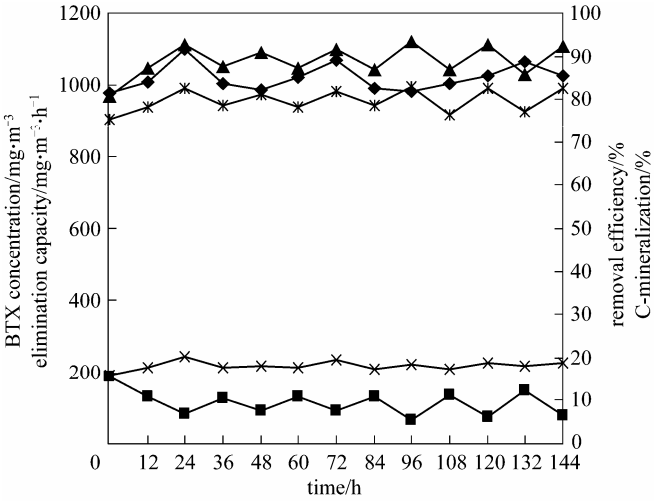
toluene, *m*- and *p*-xylene [24], peat biofilter for toluene, ethylbenzene and xylene by Gabaldon *et al*. [25], biofilter under thermophilic and mesophilic condition by Mohammad *et al*. for BTEX [3], Vermiculat-activated carbon biofilter by Ortiz *et al*. for BTX vapors [22] and trickle bed biofilter by Lu *et al*. for BTEX [23] were reported as 36.2, 146, 26.9, 218, 218, 260 and 96 g·m^{-3}·h^{-1}, respectively. In TPPB, the nominal EC of 63 g·m^{-3}·h^{-1} for benzene and 51 g·m^{-3}·h^{-1} for toluene were reported by Davidson and Daugulis [26]. In their study [26], the content of organic phase was 33% which was higher than 5% of this study. But the biomass concentration in their work was less than that of this study. In comparison to previous studies, the bioreactor has higher EC and ability for biodegradation of higher BTX concentration. The pressure drop was very low (close to 0) and the bed clogging was not happened for this reactor, while the pressure drop and bed clogging were two problems in other bioreactors. Continues exchange of nutrient mineral and requirement of additive oxygen in high inlet concentration of BTX (>1 g·m^{-3}) are two limitation of this bioreactor. Based on our findings, 75%−83% of C-BTX degraded at continues operation of bioreactor was served to as C-CO_2 and residual, which has been utilized for cell production.

Biomass and BTX concentrations in the liquid phase were also measured each 12 hours. Through 24 h, 60−100 ml of reactor solution was exchanged with fresh nutrient. This exchanging helped to a high performance operation of bioreactor [9, 11]. The results of BTX measurements in the liquid phase showed that the microorganisms in liquid phase were very active and a significant amount of introduced BTX was biodegraded. In comparison to content of introduced BTX to bioreactor, 6.4 mg·L^{-1} of BTX concentration in the liquid phase is very low after weekly operation of reactor. The amount of dissolved oxygen at this period was in the range of 84.1%−89.1%, which was sufficient for aerobic condition of cell activity.

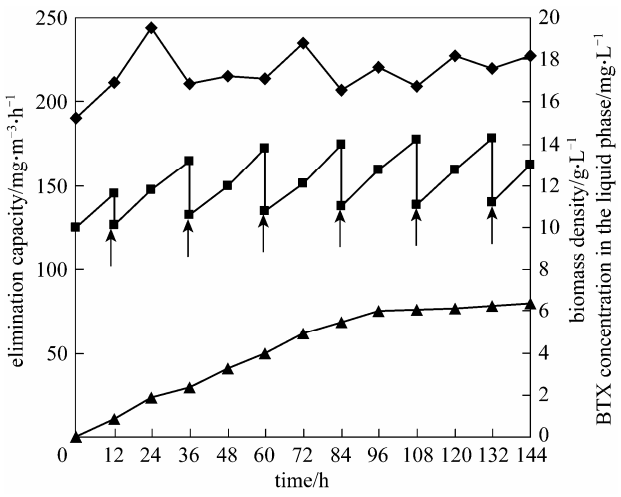
The previous foam bioreactor was applied for one pollutants as carbon source of microorganism [11, 12, 21] while in this study, capability of foamed bioreactor for simultaneously preset of three vapors was studied and demonstrated.

4 CONCLUSIONS

The ability of bioactive foamed emulsion bioreactor for treatment of BTX has successfully confirmed. The reactor potential to treat BTX for short and long



(a) Changes of EC, RE and C-mineralization (C-mineralization is the percent of C-CO_2/C-BTX degraded)
◆ influent; ■ effluent; × elimination capacity; ▲ removal efficiency; ✳ C-mineralization



(b) Changes of the elimination capacity, biomass concentration and BTX concentration in the liquid phase (The arrow indicates feeding of nutrient medium to bioreactor)
◆ elimination capacity; ■ biomass concentration; ▲ BTX concentration in the liquid phase

Figure 7 The continuous operation of bioreactor
(Operation conditions: 5% *n*-hexadecane as organic phase, 0.2% Triton X-100 as surfactant, residence time of 15 s, biomass concentration of 10−14 g·L^{-1}, oxygen content in inlet air of 40%)

period was demonstrated. In the previous studies, only individual compound (generally toluene) was utilized as model contaminant at foam reactor，while in this research potential of foam reactor was evaluated for biodegrading of complex mixture of VOCs. In the tested bioreactor herein, the mass transfer of BTX from the gas to the liquid phase was fast due to the increased interfacial surface area of the surfactant foams. In addition, the pollutants solubility was increased by increasing the organic phase concentration. The optimum residence time (15 s) of the bioreactor was less than biofilters and biotrickling filters. The low residence time increased the EC of bioreactor. The results showed that the reactor was flexible for high concentration of pollutant, especially by adding a second immiscible phase to the culture medium. The effect of various operation parameters (oxygen content, residence time, organic phase concentration and culture density) of bioreactor was investigated on the removal efficiency and elimination capacity of bioreactor and optimum conditions for continuous operation of bioreactor were determined. The determined nominal and maximum ECs for this bioreactor are higher than those of the biofillter and biotrickling, while the bed clogging and pressure drop were not encountered for this reactor. Furthermore, low RE for high inlet concentration of pollutants was resolved by using immiscible organic phase. At higher inlet BTX concentration and higher culture density, oxygen limitation occurred. By providing additive oxygen and periodical exchanging of nutrient medium, these restrictions could be resolved. Overall, with respect to the results of this and similar studies, it showed that the bioactive foamed emulsion reactor can be considered as an alternative for classic bioreactors in the future.

REFERENCES

1 Chen, C.L., Fang, H.Y., Shu, C.M., "Source location and characterization of volatile organic compound emissions at a petrochemical plant in kaohsiung Taiwan", *J. Air Waste Manage. Assoc.* **55**, 1487−1497 (2005).
2 Paca, J., Klapkova, E., Halecky, M., Jones, K., Soccol., C.R., "Performance evaluation of a biotrickling filter degrading mixtures of hydrophobic and hydrophilic compounds", *Clean Techn. Environ. Policy*, **9**, 69−74 (2007).
3 Balsam, T.M., Veiga, M.C., Kennes, C., "Mesophilic and thermophilic biotreatment of BTEX-polluted air in reactors", *Biotech. Bioeng.*, **97** (6), 1423−1438 (2007).
4 Kahraman, H., Gecki, H., "Degrading of benzene, toluene and xylene by pseudomonasaeruginosa engineered with the vitreoscilla hemoglobin gene", *Eng. Life Sci.*, **5** (4), 363−368 (2005).
5 Li, L., Liu, J.X., "Removal of xylene from off-gas using a bioreactor containing bacteria and fungi", *Int. Biodet. Biodeg.*, **58**, 60−64 (2006).
6 Choi, S.C., Oh, Y.S., "Simultaneous removal of benzene, toluene and xylenes mixture by a constructed microbial consortium during biofiltration", *Biotech. Lett.*, **24**,1269−1275(2002).
7 Torkian, A., Dehghanzadeh, R., Hakimjavadi, M., "Biodegradation of aromatic hydrocarbons in a compost biofilter", *J. Chem. Technol. Biotechnol.*, **78**, 795−801 (2003).
8 Abu Hamed, T., Bayraktar, E., Glu, U.M., Glu, T.M., "The biodegradation of benzene, toluene and phenol in a two-phase system", *Biochem. Eng. J.*, **19**, 137−146 (2004).
9 Kan, E., Deshusses, M.A., "Continuous operation of foamed emulsion bioreactors treating toluene vapors", *Biotechnol. Bioeng.*, **92** (3), 364−371 (2005).
10 Boudreau, N.G., Daugulis, A.J., "Transient performance of two-phase partitioning bioreactors treating a toluene contaminated gas stream", *Biotechnol. Bioeng.*, **94** (3), 448−457(2006).
11 Kan E., Deshusses, M.A., "Development of foamed emulsion bioreactor

for air pollution control", *Biotechnol*. *Bioeng*., **84** (2), 240−244 (2003).
12 Song, J., Kim, Y., Son, Y., Khim, J., "A bioactive foam reactor for the removal of volatile organic compounds: system performance and model development", *Bioproc*. *Biosys*. *Eng*., **30**, 439−446 (2007).
13 Shareefdeen, Z., Sing, A., Biotechnology for Odor and Air Pollution Control, Springer, New York (2004).
14 Cherry, R.S., Thompson, D.N., "The shift from growth to nutrient-limited maintenance kinetics during acclimation of a biofilter", *Biotechnol*. *Bioeng*., **56**, 330−339 (1997).
15 Gabriel, D., Deshusses, M.A., "Retrofitting existing chemical scrubbers to biotrickling filters for H_2S emission control", *Proc*. *Natl*. *Acad*. *Sci*. *U*.*S*.*A*., **100** (11), 6308−6312 (2003).
16 Daugulis, A.J., "Two-phase partitioning bioreactors: A new technology platform for destroying xenobiotics", *Trend in Biotech*., **19** (11), 457−462 (2001).
17 Davidson, C.T., Daugulis, A.J., "The treatment of gaseous benzene by two-phase partitioning bioreactors: A high performance alternative to the use of biofilters", *Appl*. *Microbiol*. *Biotechnol*., **62**, 297−301 (2003).
18 Yeom, S.H., Dalm, M.C.F., Daugulis, A.J., "Treatment of high-concentration gaseous benzene streams using a novel bioreactor system", *Biodeg*, **14**, 415−421 (2003).
19 Kan, E., Deshusses, M.A., "Cometabolic degradation of TCE vapors in a foamed emulsion bioreactor", *Environ*. *Sci*. *Technol*., **40** (3), 1022−1028 (2006).
20 Phipps, D.W., "Biodegradation of volatile organic contaminants from air using biologically activated foam", US Pat., 5714379 (1998).
21 Gyu, G.W., "Bioactive foam reactor for enhanced biological degradation specific", In: Proceeding of the 41st Meeting of KOSAE, Korean Society for Atmospheric Environment, 82−84 (2006).
22 Ortiz, I., Revah, S., Auria, R., "Effects of packing material on the biofiltration of benzene, toluene and xylene vapours", *Environ*. *Tech*., **24**, 265−275 (2003).
23 Lu, C., Chu, W., Lin, M.R., "Removal of BTEX vapor from waste gases by a trickle bed biofilter", *J*. *Air Waste Manage*. *Assoc*., **50**, 411−417 (2000).
24 Oh, Y.S., Choi, S.C., "Selection of suitable packing material for biofiltration of toluene, *m*- and *p*-xylene vapors", *J*. *Microb*., **38** (1), 31−35 (2000).
25 Gabaldon, C., Martinez, S.V., Martin, M., "Removal of TEX vapours from air in a peat biofilter: Influence of inlet concentration and inlet load", *J*. *Chem*. *Techn*. *Biotech*., **81**, 322−328 (2006).
26 Davidson, C.T., Daugulis, A.J., "Addressing biofilter limitations: A two-phase partitioning bioreactor process for the treatment of benzene and toluene contaminated gas streams", *Biodegradation*, **14**, 415−421 (2003).