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The Treatment of Waste-air Containing Mixed Solvent using a Biofilter: 1. Transient Behavior of Biofilter to Treat Waste-air Containing Ethanol

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Abstract–Transient behavior of a biofilter packed with mixed media (of granular activated carbon and compost) inoculated with a pure culture of *Pseudomonas putida* was observed at the height of each sampling port to treat waste-air containing ethanol. In addition, flooding effects of an excess supply of buffer solution was observed at each sampling port of the biofilter until it recovered the status prior to the flooding. Unlike previous investigations, various process conditions were applied to successive biofilter runs in order to monitor the corresponding unsteady behavior of the biofilter in this work. In early stage of biofilter run the removal efficiency of ethanol maintained almost 100%. However, it began to decrease when inlet load surpassed 100 $g/m^3/h$ consistent with maximum elimination capacity. At the end of biofilter-run removal efficiency was decreased and maintained at 40%. The results of this work were compared to those of such biofiltration studies as the work of Christen et al. from the point of view that pure cultures of microorganism were used in both works. Except for the period of flooding effect of the 2nd stage, the inlet load and removal efficiency continued at 105.5 $g/m^3/h$ and 95%, respectively, while they were 93.7 $g/m^3/h$ and 95%, respectively, according to the result of Christine et al.. Removal efficiency remained at 90% for the beginning period of 3 days of the 3rd stage, and it gradually decreased to 60% for remaining 5 days of the stage with an inlet load of 158.26 $g/m^3/h$, which may be interpreted as better than the result of Christine et al. Their result was that the removal efficiency on the inlet load of 154 $g/m^3/h$ of ethanol was continued to be 60% for 6 days of a separate biofilter run and decreased to 40% later. Thus, with similar inlet loads of ethanol, removal efficiency of this work was equivalent to or higher than that of Christine et al..

Key words: Biofilter, Ethanol, Transient Behavior, Removal Efficiency, Elimination Capacity

INTRODUCTION

Biological processes have increasingly been used to control undesirable compounds in different kinds of wastes. Among these processes, biofiltration has also emerged as a promising air pollution control technology. Biofilters excel in two main domains: in the removal of odoriferous compounds [Hirai et al., 1990; Eckhart, 1987; Lee et al., 2000; Islander et al., 1991; Oyarzun et al., 2003; Cho et al., 2000; Wani et al., 1998; Chung et al., 1996a, b, 2001] and in the elimination of volatile organic compounds [Ottengraf, 1986; Deshusses et al., 1995; Deshusses and Hamer, 1993; Deshusses and Dunn, 1994; Lim and Lee, 2003; Buchner, 1989; Leson and Winer, 1991; Sorial et al., 1995; Leson and Smith, 1997; Swanson and Loehr, 1997; Ottengraf and van den Oever, 1983; Zarook and Baltzis, 1994; Mohseni and Allen, 2000; Tang et al., 1995; Jorio et al., 1998; Hodge and Devinny, 1994, 1995; Shim et al., 1995; Arulneyam and Swaminathan, 2000; Auria et al., 1998; Christine et al., 2002], primarily solvents, from waste air. Under optimum conditions, the pollutants are fully biodegraded without the formation of aqueous effluents. Bioreactors are reactors in which a humid polluted airstream is passed through a porous packed bed on which pollutant-degrading microbial cultures are naturally immobilized. The technology consists of exploring the contaminated air to a moist film of microbes attached to a stationary synthetic or natural support medium. The VOCs (volatile organic compounds) in the contaminated air sorb into or onto the surfaces of the bed medium long enough for the biodegrading microbes to oxidize the VOCs, converting them into environmentally benign end products such as H_2O and CO_2. Using ambient microbial oxidation to treat large volumes of air with low concentrations of biodegradable VOCs makes biofiltration technology a more cost-effective process, compared to other VOC control technologies such as carbon adsorption and incineration. Thus biological waste air treatment processes offer a cost-effective solution for the treatment of large volumetric air-streams containing low levels of pollutants [Ottengraf, 1986; Sorial et al., 1995].

While 129 kinds of organic compounds have been designated as priority pollutants and have become subjected to regulatory control by Environment Protection Agency (EPA) in United States [Metcalf and Eddy Inc., 1996], 31 kinds of VOCs including methanol, ethyl alcohol, butane, gasoline and TCE (trichloroethylene) have been designated as priority regulatory VOCs and their emissions have become subject to regulatory control in Korea. Then it becomes inevitable to treat large volumetric air-streams containing low levels of VOCs, which is economically disadvantageous to recover.

In the present work, the authors chose relatively toxic ethanol which is often used in various industries, including the food industries, and is emitted considerably from bakeries, distilleries and foundries as target VOC. Then each transient behavior of biofilter packed with mixed media (of granular activated carbon and compost) inoculated with a pure culture of *Pseudomonas putida* is observed at the height of each sampling port to treat waste-air containing etha-

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nol. Previous study done by Hodge et al. [Hodge and Devinny, 1994, 1995] used soil from a petroleum refinery as bacterial consortia and adopted granular activated carbon or compost separately as packing material in separate biofilter experiments performed under fixed operation conditions. Shim et al. [1995] performed biofilter-experiments using microbial consortia from activated-sludge-microorganism in fixed film spiral bioreactor. Arulneyam and Swaminathan [2000] also adopted microbial consortia from activated sludge with the packing media of compost and polystyrene. Auria et al. [1998] investigated ethanol biotreatment using microbial consortia from VOC treating a biotrickling filter with the packing media of peat. Christen et al. [2002] investigated ethanol biofiltration of three separate runs with packing media of sugar cane bagasse inoculated with a pure culture of *Candida utilis*. Unlike their investigation, various process conditions are applied to successive biofilter runs in order to monitor and correlate each corresponding unsteady behavior of the biofilter at the height of each sampling port. In addition, flooding effects of excess supply of buffer solution are observed at each sampling port of the biofilter until it recovers the status prior to the flooding in this work. The result of this work is compared to such biofiltration studies as the work of Christen et al. [2002] from the point of view that pure cultures of microorganism were used in both works. It shall be used as control to observe the biofilter behavior for the treatment of waste-air containing both hydrophobic solvent (toluene) and hydrophilic solvent (ethanol) in part two of the future work.

MATERIALS AND METHOD

1. Biofilter Design and its Apparatus

The experiment to treat waste-air containing hydrophilic ethanol was performed to observe transient behavior of biofilter. The biofilter reactor was manufactured in a way that feed gas entered from the top of the biofilter composed of two acryl tubes (diameter: 5 cm, length: 25 cm) connected in series. Upper and lower reactor tubes were packed up to 18 cm and 20 cm from their bottom with media, respectively, so that total effective height of biofilter was adjusted to 38 cm. Among four sampling ports of the biofilter the 1st one, 2nd one and 3rd one were positioned at 10 cm below the top surface of the upper media, 2 cm below the top surface of the lower media and 12 cm below the top surface of the lower media, respectively. The fourth one was positioned at the exit of the biofilter. Therefore, the ratios of effective height to total were 0.26, 0.53, 0.79 and 1.0 for 1st one, 2nd one, 3rd one and 4th one, respectively.

In a biofilter, a mixture of equal volume of granular activated carbon and compost with an average radius of 3 mm and 0.6 mm, respectively, was used as the packing media of the biofilter. Granular activated carbon chosen as supporting material of the packing media has shortcomings of frequent channeling and short circuiting with increased pressure drop resulting from microsomal growth, while it has the advantage of high buffer capacity against sudden shock loading owing to high adsorption capacity. Nutrition necessary for the growth of microorganism was provided by organic packing media, i.e., compost. In addition, buffer solution was intermittently provided from the top of the biofilter in order to maintain the optimum pH and moisture conditions.

Air provided by a blower (Young Nam Yasunnaga, outlet pressure: 0.12 kg_f/cm^2; maximum flow rate: 43 L/min) passed through a series of three humidifier columns maintained at 40-50 °C by thermostat (Jeil Science, J-PW B2), and its relative humidity was maintained at 95-99%. Variously adjusted amounts of ethanol were continuously injected by syringe pump (KD Scientific, Model: KDS200) into a heated conduit of 140 °C through which humidified air passed. Waste-air containing ethanol of variously designed concentrations was artificially manufactured in this way and was provided to the top of the biofilter. Tygon tubing was used to convey pure air and a viton tube was used to transport manufactured waste-air containing ethanol as feed gas to the biofilter. Temperature of biofilter column was maintained at 26-40 °C by heating band to simulate the temperature-variation of the biofilter in the field in consideration of natural temperature disturbance and swagelok fitting was used for all fittings. A schematic diagram of biofilter process is shown as Fig. 1.

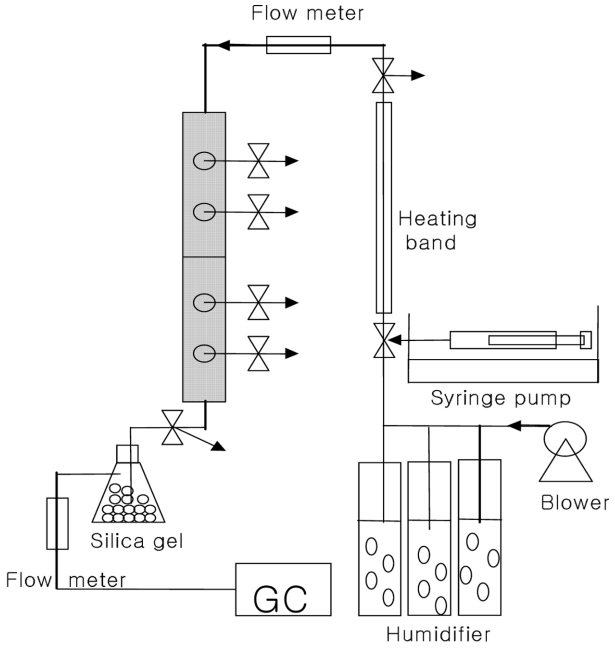

Fig. 1. Schematic diagram of biofilter.

2. Microorganism, Inoculum Preparation, Bacteria Count

Pseudomonas putida (KCTC 1768) was incubated in the following way. Eight grams of nutrient broth was dissolved in demineralized water of pH 7 and sterilized at 121 °C for 15 minutes by autoclave to make liquid-medium. Small quantity of the medium was poured and agar was added to attach solid-medium on the surface of a petri-dish where Pseudomonas putida was smeared. Microorganisms on the petri-dish, which weretaken by loop transfer needles and which were dropped into prepared medium in flask, were incubated under the condition of 26 °C and 200 rpm set by shaking incubator. Microorganisms were inoculated, when the absorbance of the medium representing optical density measured every 3 hr at the wave length of 600 nm by UV-Visible spectrophotometer exceeded 0.8, on the packing media of biofilter by recycling the incubated microorganism with the medium into biofilter at the rate of 0.4 ml/min for 48 hrs.

Microbial count fixed on packing media was determined in the following way. One gram of packing media was vortexed with 5 ml of sterilized demineralized water and it was ground in 5% paraform-

aldehyde solution for 48 hrs. The ground sample was 10 times diluted and was filtered with polycarbonate membrane filter (pore size 0.2 μm, ϕ25 mm) by 1 ml at a time and the filter was dried. The dried filter was placed on slide glass and was stained by 10 μl of DAPI (4'-6-diamidino-2-phenylindole, 0.33 mg/ml) for 1 hr in a dark box. After the stained filter was washed and was dried, each drop of fluoroguard-antifade-reagent was dropped on each side of the stained filter. It was coved with cover glasses and was observed by fluorescence microscope (Axiolab, Xeiss, Germany) UV filter (G365, LP395, FT420). The total bacterial number (TBN) was calculated by formula as below.

$$\text{TBN(total bacterial number)} = \frac{A_0 \times F_1}{F_2 \times F_3}$$

A_0: Average cell number in field
F_1 : Filter area
F_2 : Field area
F_3 : Filter sample volume

3. Analytical Methods

Concentrations of ethanol were measured in the following way at the positions of feed and four sampling ports. A gas chromatograph (Shimazu, GC-17AAFw Ver.3) equipped with flame ionization detector (FID) and SUPELCO WAX^{TM}-10 fused silica capillary column (30 m×0.53 mm×2.0 μm) was calibrated with ethanol standard gas (99.8 ppmv) purchased from RIGAS. After each 100 μL of ethanol gas was taken by 250 μL gas-tight-syringe (Hamilton, USA) from feed or each sampling port, it was injected through the injector. Then the concentration of ethanol was calculated at the peak of its retention time. Nitrogen (99.999%) was used as carrier gas and its flow rate was 4 ml/min. Operating temperatures of injector, oven (column) and detector were 200 ℃, 90 ℃ and 250 ℃, respectively. Activity of microbes in the biofilter was periodically observed by measuring the concentration of carbon dioxide generated by biodegradation of ethanol with gas analyzer (Siemens, Ultramat 23).

4. pH, Density, Moisture

The optimum control of pH and moisture of the packing media in the biofilter reactor is definitely necessary for adequate operation of biofilter. Buffer solution was intermittently supplied at the rate of 0.4 ml/min by peristaltic pump (Masflex) to maintain the optimum pH of packing media. Each twenty grams of media sample was taken from each samplimg port to place in a vacuum dry oven (Sam Heung) for 24 hrs at 105 ℃ and to measure the dried weight of the sample. The moisture content of the media was calculated by the difference of its weight between before and after drying. Density of the media was measured on basis of equal volume mixture of granular activated carbon (25 ml) and compost (25 ml).

5. Biofilter Experiment

5-1. Process Condition

For 4 days (8 times) of biofilter operation (i.e., 1st stage of operation) air was supplied at the rate of 0.25 L/min and ethanol was injected by syringe pump (KD Scientific, Model: KDS200) into air passing through preheated conduit at the rate of 0.83 μL/min. Theoretical ethanol concentration of manufactured waste-air was 1,450 ppmv, assuming it was ideal gas. At the 2nd stage of biofilter operation (9-26 times) the same ethanol concentration was maintained as that of the 1st stage of operation. However, air supply rate and ethanol injection rate were increased by a factor of two to be 0.5 L/min and 1.67 μL/min, respectively, so that ethanol inlet load was doubled. During the 3rd stage (27-42 times) air-supply rate was kept the same as 0.5 L/min and ethanol injection rate was increased, by factor of 1.5, up to 2.5 μL/min. Therefore, theoretical ethanol concentration was increased by factor of 1.5 to be 2,180 ppmv in the same way as inlet load was. At 4th stage of operation (43-58 times), process conditions, except for temperature of biofilter, were maintained as the same as those of the 3rd stage of operation. (In the middle of the 4th stage of biofilter operation temperature was increased by 5 ℃) At the 5th stage of operation (59-77 times) ethanol injection rate and air supply rate were increased by factor of two to be 5 μL/min and 1 L/min, respectively. Therefore, ethanol concentration remained as the same as that of the 4th stage of operation to be 2,180 ppmv. However, the ethanol inlet load was increased by factor of two. Operating conditions and temperature schedule of biofilter are shown as Fig. 2 and Table 2, respectively.

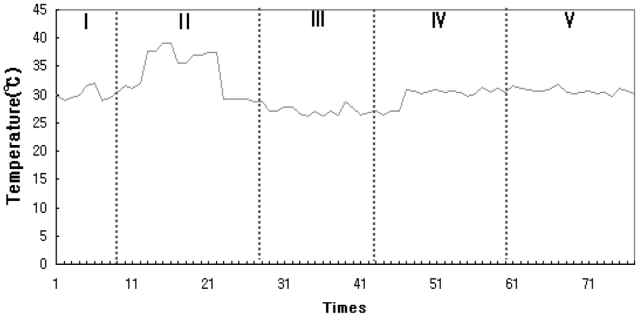

Fig. 2. Temperature schedule for the operation of biofilter.

5-2. Buffer Solution

The solutions, as shown in Table 1, were mixed in such a fixed proportion as [salt stock solution (100 ml)+$CaCl_2 \cdot 2H_2O$ (10 ml)+$MgSO_4 \cdot 7H_2O$ (10 ml)+sterilized distilled water (880 ml)] to make 1 liter of the buffer and mineral medium. As in Fig. 3, an excess amount of 45 ml buffer solution (M9 solution, Table 1) was provided at the rate of 0.4 ml/min to biofilter on 18 times of biofilter-operation by peristaltic pump (Masterflex). The excess supply of buffer solution was designed to observe the effects of flooding such as temporary decrease of removal efficiency due to loss of interface between waste-air and bio-layer resulting in decrease of effective height of biofilter. Transient behavior of biofilter to recover the status prior to flooding was also an important phenomenon to observe. Afterwards, 10 ml of buffer solution was provided intermittently at the same rate. Microbes were from time to time provided to the biofilter when the activity of microbes attached to media turned out to be decreased, which may be measured with the concentration of carbon dioxide.

Table 1. Compositions of buffer solution

Salt stock solution		Mineral solution	
$NaHPO_4$	70 g/L	$CaCl_2 \cdot 2H_2O$	0.37 g/250 ml
KH_2PO_4	30 g/L	$MgSO_4 \cdot 7H_2O$	6.16 g/250 ml
NaCl	50 g/L		
NH_4Cl	10 g/L		

Table 2. Theoretical values of operating condition from each stage of biofilter

Theoretical value \ Stage (times)	1st stage (1-8)	2nd stage (9-26)	3rd stage (27-42)	4th stage (43-58)	5th stage (59-77)
$\dot{m}$ (μl/min)	0.83	1.67	2.5		5.0
Q (L/min)	0.25	0.5	0.5	0.5	1.0
C_{go} (ppm)	1,450	1,450	2,180	2,180	2,180
C_{go} (g/m^3)	2.62	2.62	3.93	3.93	3.93
τ (min)	2.98	1.49	1.49	1.49	0.75
Inlet load (g/m^3/h)	52.75	105.50	158.26	158.26	316.51

※ $\dot{m}$: ethanol injection rate at a syringe pump
Q: air flow rate
C_{go}: feed concentration
τ: EBCT (effective height of biofilter: 0.38 m)

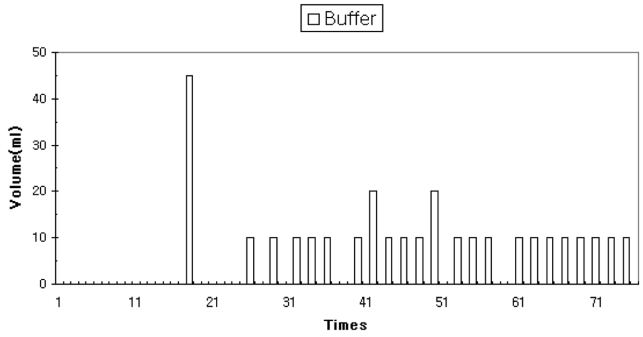

Fig. 3. Feeding schedule of buffer solution to biofilter.

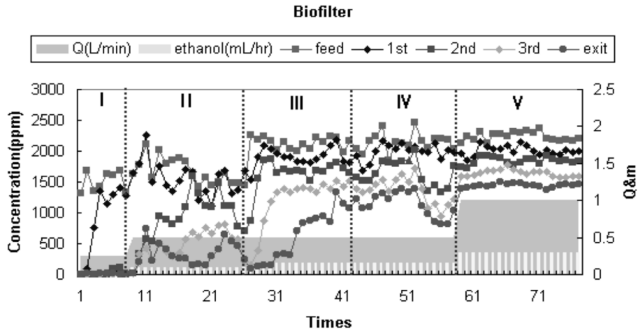

Fig. 4. Various ethanol concentrations of biofilter at each sampling port versus experimental times.

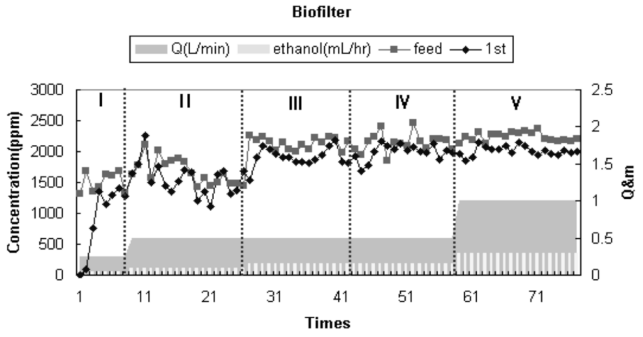

Fig. 5. Various ethanol concentrations of biofilter at feed inlet and 1st sampling port.

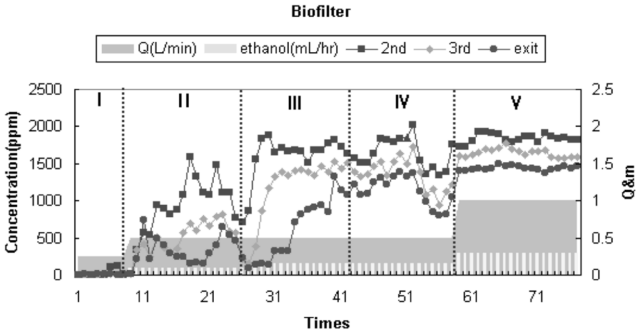

Fig. 6. Various ethanol concentrations of biofilter at 2nd, 3rd and exit sampling ports.

RESULTS AND DISCUSSION

1. Time Evolutions of Ethanol Concentrations at Four Sampling Ports

Transient behavior of ethanol concentrations measured at the position of feed inlet and four sampling ports of biofilter, is shown as in Fig. 4 when the biofilter was run at 26-40 °C under various operating conditions as shown in Table 2 for 39 days (total 77 times with measuring frequency of two times per day). Biological activity approximately doubles for each 10 °C rise in temperature up to an optimum temperature of about 37 °C for mesophyllic bacteria [Bohn, 1977; William and Miller, 1992]. The concentrations of ethanol measured at the position of feed inlet and 1st sampling port, and 2nd, 3rd and 4th sampling port (exit) are shown as in Figs. 5 and 6, respectively.

During 4 days (8 times) after start-up of the biofilter, transient behavior of all breakthrough curves, except for 1st and 2nd sampling ports, showed that ethanol was continuously adsorbed on the media, and adsorption of ethanol was under way since the theoretical inlet load of the 1st stage operation was the lowest of 52.75 g/m^3/h. At the 2nd stage of biofilter operation (9-26 times), both rates of ethanol injection and air supply were increased by a factor of two that ethanol concentration remained the same. However, reduced retention time due to increased rate of air-supply resulted in less removal efficiency, as shown in Fig. 7, than that at the 1st stage of operation. Increased inlet load was attributed to that increased rate of air supply with same ethanol concentration which resulted in reduced retention time.

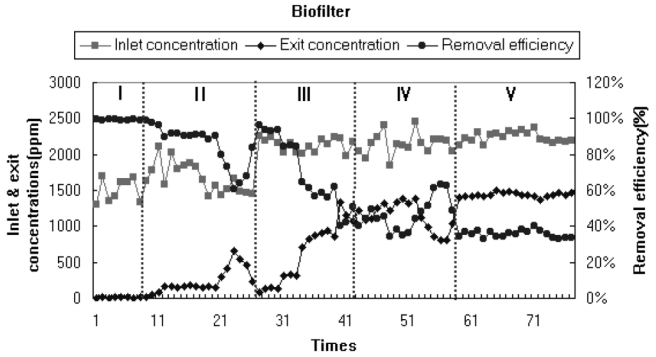

Fig. 7. Removal efficiency, inlet and exit concentrations versus times.

After excess amount of 45 ml buffer solution was poured into the biofilter at 18 times of 2nd stage operation (9-26 times) of the biofilter, an abnormal largest concentration peak appeared first at the 1st sampling port. For the lower sampling port, a less abnormal peak appeared later with a time interval than that of the upper sampling port as shown in Figs. 4, 5 and 6. It was observed that removal efficiency was diminished due to such flooding effects of excess supply of buffer solution as temporary loss of interface between waste-air and bio-layer and reduced effective height of biofilter as shown in Fig. 7. Later, the removal efficiency was observed to recover the status prior to flooding. Except for the period of flooding effect of the 2nd stage, the inlet load and removal efficiency was continued at 105.5 g/m3/h and 95%, respectively, while they were 93.7 g/m^3/h and 95%, respectively, according to the result of Christen et al. [2002].

The biofilter was run at a temperature between 26-30 °C during the 3rd stage (27-42 times) of a run when retention time was maintained as the same as that of the 2nd stage of the run and both feed concentration and inlet load of ethanol were increased to 1.5 times. It is shown in Fig. 4 that the order of saturation by adsorption from each unsteady behavior of breakthrough curve was in such way as 1st, 2nd, 3rd and 4th sampling port were in the 1st, 2nd, 3rd and 4th place, respectively. The sooner a breakthrough curve reached the status of saturation by adsorption, the higher was its ethanol concentration of waste-air passing through the position of its sampling port. Removal efficiency remained at 90% for the beginning period of 3 days of the 3rd stage and it gradually decreased to 60% for remaining period of 5 days of the stage with the inlet load of 158.26 g/m^3/h, which may be interpreted as the better one than the result of Christen et al. [2002]. Their result was that the removal efficiency on the inlet load of 154 g/m^3/h of ethanol was continued to be 60% for 6 days of a separate biofilter run and decreased to 40% later.

At the 4th stage of operation (43-58 times), process conditions, except for temperature of biofilter, were maintained as the same as those of the 3rd stage. Operating temperature was maintained at 26 °C. However in the middle of the 4th stage the temperature was increased to 30 °C, as in Fig. 2, so as to enhance removal efficiency of ethanol. As a result, each time-evolution of ethanol concentration at each sampling port was observed lowered, as in Fig. 4, at the 2nd half of the 4th stage of biofilter. Thus removal efficiency of ethanol was enhanced as in Fig. 7.

Time-evolutions of ethanol concentrations at 3rd and 4th stages of biofilter-run were designed as controls to the corresponding-stages with an additional operating condition on toluene as well as the same one on ethanol as in Table 2 for the treatment of waste-air containing both hydrophobic solvent (toluene) and hydrophilic solvent (ethanol) in part two of the future work.

At the 5th stage of biofilter-run, the feed concentration of ethanol was the same as that at the 4th stage of the run and its retention time was reduced by half so that its inlet load was increased by a factor of two. Consequently, each breakthrough curve at each sampling port showed more rapid increase and maintained new steady-state concentration, which suggested that it approached a new state of saturation. During 9 days of the 5th stage, the inlet load and removal efficiency was continued to be 316.51 g/m^3/h and 40%, respectively, while the inlet load was 512 g/m^3/h and removal efficiency was continuously decreased to 50% for only 2 days separate biofilter-operation according to the result of Christen et al. [2002]. However, the result of Christen et al. [2002] may be attributed to the effect of adsorption on packing media for separate biofilter run, and there was a tendency that the removal efficiency may be further decreased for prolonged biofilter operation. Table 3 shows the comparison between the results of this work and those of Christen et al. [2002].

Time-evolutions of removal efficiency and elimination capacity versus inlet load are shown as in Figs. 7 and 8, respectively. In early time-evolution of removal efficiency as in Fig. 7, it maintained almost 100%. However, it began to decrease when inlet load surpassed, as in Fig. 8, 100 g/m^3/h consistent with maximum elimination capacity shown as in Fig. 9. At the end of a biofilter-run, removal efficiency was decreased and maintained at 40%. This value of maximum elimination capacity turned out to be lower than 195 g/m^3/h from the result of Arulneyam and Swaminathan [2000] and 185 g/m^3/h from that of Shim et al. [1995]. It may be attributed to the frequent and relatively large change in operating temperature of the biofilter dis-

Table 3. Comparison of biofilter performance between this work and Christine et al. [2002]

	Inlet load (g/m^3/h)	Removal efficiency (%)	Retention time (min)	Operating temperature (°C)	Duration (day)
Lim and Park	105.5	95	1.49	30-38	4 (except for flooding period)
	158.3	60	1.49	26-30	8
	316.5	40	0.75	30	9
Christine	93.7	95	6	30	12
et al. [2002]	154	60	6	30	6
	512	50	6	30	2

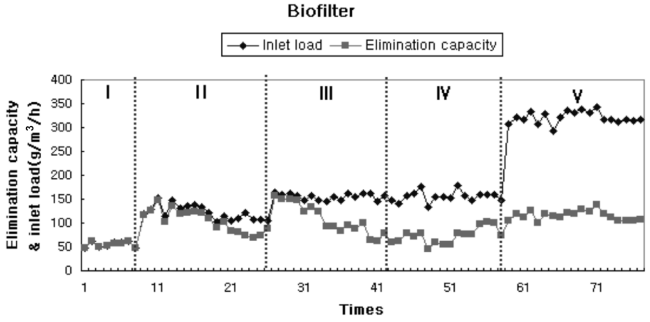

Fig. 8. Elimination capacity (g/m^3/h) and inlet load versus times.

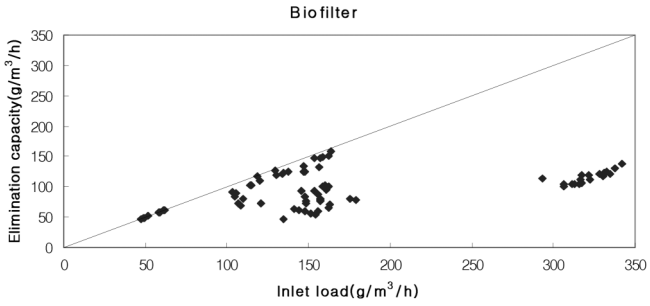

Fig. 9. Elimination capacity (g/m^3/h) versus inlet load of ethanol at the exit of biofilter.

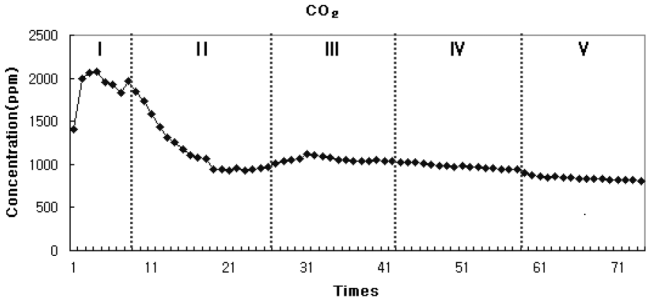

Fig. 10. Time evolution of carbon dioxide generation.

rupted the biological system and decreased overall performance of this work. It may be also attributed to channeling or short circuiting caused by incipient flooding which decreased its performance. However, it was higher than *circa* 30 g/m^3/h of maximum elimination capacity from the study of Auria et al. [1998]. It should be remembered that they used microbial consortia from activated sludge instead of such a pure culture as that of Christen et al. [2002] as well as that of this work. Carbon dioxide generated from biofilter is shown as in Fig. 10.

2. Analysis of Packing Media

2-1. Density

The density of an equal volume mixture of granular activated carbon and compost was 0.38.

2-2. pH and Moisture Content

The pHs of packing media from the 2nd and 4th sampling ports were the same as 7 at the beginning of the biofilter experiments. However, they changed to 5.85 and 6.09 at the end of biofilter experiments, respectively. Dried weights of the media from the 2nd and 4th sampling ports were 10.33 g and 9.31 g (weight of the media before drying was 20 g), by which moisture contents of the media from the 2nd and 4th sampling ports turned out to be 48.36% and 53.44%, respectively.

2-3. Microbial Counts

The total bacterial numbers (TBN) for the 1st, 2nd and 3rd sampling ports turned out to 1.33×10^9/g, 7.22×10^8/g and 4.68×10^8/g, respectively. Thus, the microbial distribution in the biofilter was in the way that total bacterial number (TBN) was decreased as the effective height of the position of the sampling port was increased.

CONCLUSION

In the early stage of a biofilter run, the removal efficiency of ethanol maintained almost 100%. However, it began to decrease when the inlet load surpassed 100 g/m^3/h, consistent with maximum elimination capacity. At the end of the biofilter-run, the removal efficiency was decreased and maintained at 40%. This value of maximum elimination capacity turned out to be lower than 195 g/m^3/h from the result of Arulneyam and Swaminathan [2000] and 185 g/m^3/h from that of Shim et al. [1995]. It may be attributed to the frequent and relatively large change in operating temperature of the biofilter which disrupted the biological system and decreased overall performance of the biofilter. It may be also attributed to channeling or short circuiting caused by incipient flooding which decreased its performance. However, it was higher than circa 30 g/m^3/h of maximum elimination capacity from the study of Auria et al. [1998]. They used microbial consortia from activated sludge instead of such a pure culture as that of Christen et al. [2002] as well as that of this work. The result of this work was compared to those of such biofiltration study as the work of Christen et al. [2002] from the point of view that pure cultures of microorganism were used in both works.

After excess amount of 45 ml buffer solution was poured into the biofilter, a less abnormal peak appeared for the lower sampling port later with a time interval than that of the upper sampling port. It was observed that removal efficiency was diminished due to flooding effects of excess supply of buffer solution. Later, the removal efficiency was observed to recover the status prior to flooding. Except for the period of flooding effect of the 2nd stage, the inlet load and removal efficiency was continued at 105.5 g/m^3/h and 95%, respectively, while they were 93.7 g/m^3/h and 95%, respectively, according to the result of Christen et al. [2002]. Removal efficiency remained at 90% for the beginning period of 3 days of the 3rd stage, and it gradually decreased to 60% for the remaining period of 5 days of the stage with the inlet load of 158.26 g/m^3/h, which may be interpreted as better than the result of Christen et al. [2002]. Their result was that the removal efficiency on the inlet load of 154 g/m^3/h of ethanol continued to be 60% for 6 days of a separate biofilter run and decreased to 40% later. During 9 days of the 5th stage the inlet load and removal efficiency continued to be 316.51 g/m^3/h and 40%, respectively, while the inlet load was 512 g/m^3/h and removal efficiency was continuously decreased to 50% for only 2 days separate biofilter-operation according to the result of Christen et al. [2002]. Thus, with similar inlet loads of ethanol, the removal efficiency of this work was equivalent to or higher than that of Christen et al. [2002].

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