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SHORT COMMUNICATION

Effect of Temperature on the Performance of a Biofilter Inoculated with *Pseudomonas putida* to Treat Waste-Air Containing Ethanol

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Abstract−The microbes of *Pseudomonas putida* (KCTC1768) were fixed on the biofilter-packing media comprising an equivolume mixture of granular activated carbon (GAC) and compost, by recycling the liquid medium containing incubated *Pseudomonas putida* (KCTC1768). A biofilter experiment was performed to observe its transient behavior under the operating condition of 2,180 ppmv of ethanol-inlet concentration and 158 g/m^3/h of ethanol-inlet load for the five consecutive temperature-stages of operation ranging from 25 °C to 40 °C. For the five temperature-stages of operation their removal efficiencies were measured and were compared with each other. The optimum operating temperature of the biofilter turned out to be *ca.* 30 °C, which was consistent with the previous experimental result of Lim and Park. However, the optimum incubation-temperatures of *Pseudomonas putida* (KCTC1768) and the equivalent (i.e., NCIMB8858) were announced to be of 26 °C and 25 °C by Korea Collection for Type Cultures (KCTC) and National Collections of Industrial, Food and Marine Bacteria (NCIMB), respectively. It was also confirmed by the experiment in which the microbes were incubated in the same liquid medium as in the previous work of Lim and Park at temperature ranging from 20 °C to 40 °C and their growth rates were subsequently measured. Thus, the optimum operating temperature of a biofilter inoculated with *Pseudomonas putida* (KCTC1768) was proved to be 30 °C, which was higher than its optimum incubation-temperature by *ca.* 5 °C.

Key words: Biofilter, Waste-Air, VOC, Ethanol, Optimum Operating Temperature, Optimum Incubation Temperature, *Pseudomonas putida*

INTRODUCTION

While one hundred twenty-nine kinds of organic compounds have been designated as priority pollutants and have become subjected to regulatory control by the Environment Protection Agency (EPA) in the United States [Metcalf and Eddy Inc, 1996], thirty-one kinds of VOCs including ethanol, butane, gasoline and TCE (trichloroethylene) have been designated as priority regulatory VOCs and their emissions have become subject to regulatory control in Korea. Thus, it becomes inevitable to treat large volumetric air-streams containing low levels of VOCs, which is economically disadvantageous to recover, by the execution of regulatory controls based on total amount of emission. The technology of bio-filtration provides an economic solution for treating vast waste-air containing low concentrations of biodegradable VOCs [Ottengraf, 1986; Sorial et al., 1995].

Temperature should be controlled in all systems of biological treatment including biofilter for excellent biofilter-performance [Rozich, 1995; van Lith et al., 1990]. It has been reported that microbial activity was optimal between 22 °C and 35 °C [Leson and Winer, 1991] and in general 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]. However, VOC degradation was reportedly inhibited at temperatures above 40 °C [Lu et al., 1999]. Lim and Park [2004] performed experiments of a biofilter, in which *Pseudomonas putida* (KCTC1768) was inoculated, to observe its transient behavior finally leading to the maximum elimination capacity of *ca.* 100 g/m^3/h of ethanol within the temperature range of 26-40 °C. Yoon and Park [2002] studied the effects of gas flow rate, inlet concentration and temperature on biofiltration of nine volatile organic compounds in a peat-packed biofilter inoculated with the slurry from wastewater treatment plant. They suggested that the temperature of 32 °C became a more favorable condition (i.e., the optimum temperature) than that of 25 °C as the inlet load increased. Sa and Boaventra [2001] investigated the biodegradation of phenol by *Pseudomonas putida* DSM 548 in a trickling bed reactor in the temperature range of 19-30 °C. Thus, the proper temperature-control of a biological treatment including biofilter is very important for its excellent performance.

However the optimum operating-temperature of a biofilter inoculated with certain microbes is frequently higher than the optimum incubation-temperature for the growth of the microbes in the liquid medium. The growth characteristics and microbial metabolism of *Pseudomonas putida* (KCTC1768) or the equivalent (i.e., NCIMB8858) was investigated by Jones and Turner [1973]. According to the announcement of Korea Collection for Type Cultures (KCTC) and National Collections of Industrial, Food and Marine Bacteria (NCIMB), the optimum incubation-temperatures of *Pseudomonas putida* (KCTC 1768) and the equivalent (i.e., NCIMB8858) were 26 °C and 25 °C, respectively [Jones and Turner, 1973]. Annadurai et al. [2002] investigated the biodegradation potential of phenol using mixed liquors of *Pseudomonas putida* (ATCC 31800) and/or activated sludge so that the amount of the phenol degraded by *Pseudomonas putida*

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decreased in minimal medium when temperature increased under the range of temperature between 30-36 °C. Alagappan and Cowan [2004] evaluated the effect of temperature on the growth kinetics of *Pseudomonas putida* F1 growing on benzene and toluene in order to suggest that the optimum temperature might fall between 30 and 35 °C.

In this paper a biofilter is packed with the media inoculated with *Pseudomonas putida* (KCTC1768) and is operated under various operating temperatures in order to eliminate ethanol contained in waste-air. Then the optimum operating temperature for a biofilter-performance is evaluated and is compared with the result of Lim and Park [2004]. Subsequently, the optimum operating temperature for the biofilter-performance of *Pseudomonas putida* (KCTC1768) is compared with its optimum incubation-temperature.

EXPERIMENTAL

The biofilter equipped with four sampling ports was composed of two acrylic tubes (diameter : 5 cm, length : 25 cm) to be operated downflow in such a way that waste air is fed to its top. Each concentration of treated waste air was measured at the sampling port installed at each height of the biofilter composed of two parts (i.e., upper part and lower part). Biofilter-media in the upper part and the lower part were packed 18 cm high and 20 cm high, respectively, so that total effective height of the biofilter became 38 cm.

The equivolume mixture of granular activated carbon and compost with average diameters of 3 mm and 0.6 mm, respectively, was used as the packing media of the biofilter. The schematic diagram of the biofilter system is shown as in Fig. 1. *Pseudomonas putida* (KCTC1768) was purchased from KCTC and was incubated to be inoculated to the packing media in the same way as in Lim and Park [2004]. The concentration of ethanol and carbon-dioxide from treated waste air was also analyzed according to the same way as in Lim and Park [2004]. The experiment of a biofilter was performed to

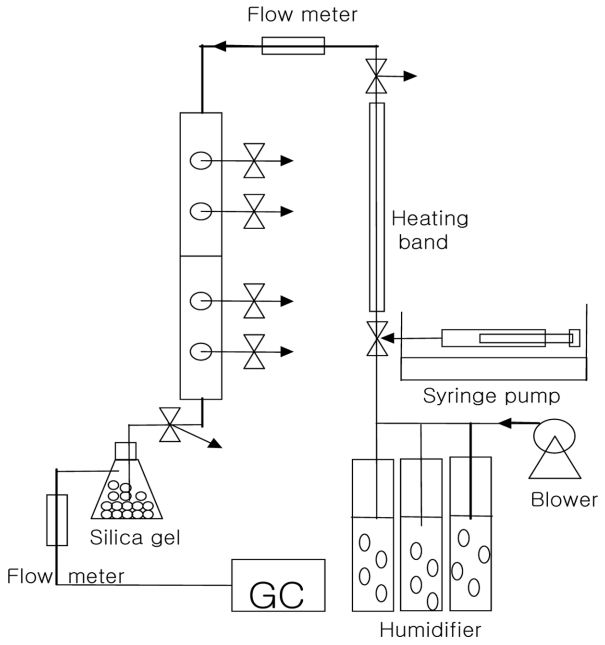

Fig. 1. Schematic diagram of biofilter.

Table 1. Theoretical values of operating condition from each stage of biofilter [Lim and Park, 2004]

Theoretical value \ Stage (times)	I (1-8)	II (9-26)	III (27-42)	IV (43-58)	V (59-77)
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} (ppmv)	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

m : ethanol injection rate at a syringe pump
Q : air flow rate
C_{go} : feed concentration
τ : retention time (Effective height : 0.38 m)

Table 2. Operating condition of each stage of biofilter-operation

Conditions \ Stage (times)	I (1-20)	II (21-30)	III (31-40)	IV (41-50)	V (51-54)
Temperature (°C)	30	25	35	30	40
C_{go} (ppmv)			2,180		
Inlet load (g/m^3/h)			158.26		

observe its transient behavior under the operating condition of 3rd stage from Table 1 [Lim and Park, 2004] for 27 days (total 54 times with measuring frequency of two times per day) according to the temperature schedule of Table 2. The 1st stage of the experiment was continued at 30 °C for 20 times of measurement that was considered enough time for adsorption to reach the state of equilibrium at four sampling ports of the biofilter. The 2nd, 3rd, and 4th stages of the experiment were continued for 10 times of measurement at 25 °C, 35 °C and 30 °C, respectively. The duration and temperature of last 5th stage of the experiment was 4 times of measurement and 40 °C, respectively.

RESULTS AND DISCUSSION

Transient behavior of ethanol concentrations, measured at the position of feed inlet and four sampling ports of the biofilter, is shown as in Fig. 2 when the biofilter was run according to each temperature-schedule as given in Table 2 at each stage of operation for 27 days (total 54 times with measuring frequency of two times per day). Time-evolutions of the removal efficiency at the exit of the biofilter is shown for the five consecutive stages of biofilter-operation as in Fig. 3.

The temperature of the biofilter was set at 30 °C at the 1st stage (1st-20th time) of the biofilter. Fig. 2 shows that at the 1st stage of operation the order of saturation by adsorption from the unsteady behavior of each breakthrough curve was in such a way that the 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 its ethanol concentration of waste-air passing through the position of its sampling

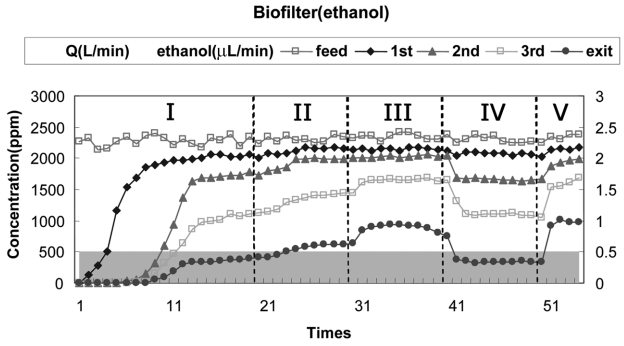

Fig. 2. Various ethanol concentrations of a biofilter at each sampling port versus experimental times

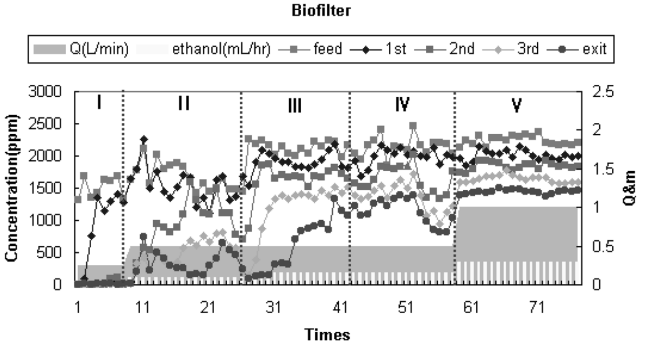

Fig. 4. Various ethanol concentrations of biofilter at each sampling port versus experimental times [Lim and Park, 2004].

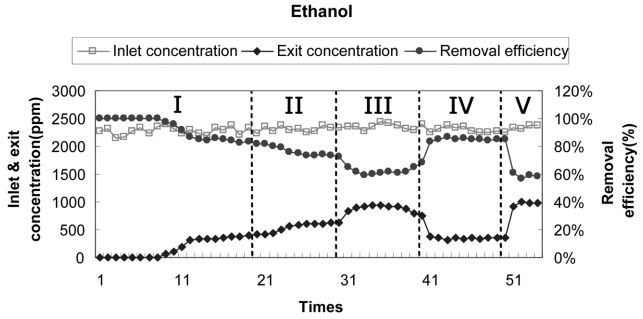

Fig. 3. Removal efficiency, inlet and exit concentrations versus times.

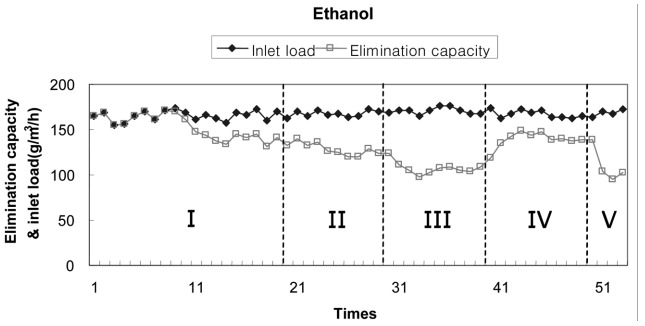

Fig. 5. Elimination capacity (g/m^3/h) and inlet load versus times.

port was. Thus, in early time-evolution (i.e., the beginning of 1st stage of operation) of the removal efficiency as in Fig. 3, it maintained almost 100% due to adsorption of ethanol molecule contained in waste air to packing media of the biofilter. However, it began to decrease to 80% of removal efficiency at the end of the 1st stage of operation as the ethanol concentration at the exit of the biofilter rose to reach the status of equilibrium due to saturation by adsorption. The temperature of the biofilter was reset to decrease to 25 °C at the beginning of 2nd stage (21st-30th time) of operation and the biofilter was kept to run. As a result, the concentration of ethanol from treated waste-air was increased until it reached the steady state to reduce the removal efficiency to *ca.* 70% as in Fig. 3. In the experiment of Lim and Park [2004] the operating temperature of a biofilter was kept at 26 °C in the beginning of 4th stage of operation from Table 1. In the 2nd half of the same stage of operation the operating temperature of the biofilter was raised to 30 °C so that the concentration of ethanol from treated waste-air at each sampling port was drastically decreased as in Fig. 4, which corresponded to the result of this experiment. It was also reported that the removal efficiency at the temperature of 32 °C was a little bit higher than or almost the same as that of 25 °C under the condition of EBRT of 1.5 min [Yoon and Park, 2002]. However, the former was reportedly much higher than the latter under the condition of EBRT of 1 min with the same inlet concentrations of nine VOCs [Yoon and Park, 2002]. Thus, it was consistent with both of the experimental results of Lim and Park [2004] and Yoon and Park [2002] that the removal efficiency at 2nd stage of operation (25 °C) was less than that at 1st stage operation (30 °C) as in Fig. 3. When the temperature of the biofilter jumped to 35 °C at the 3rd stage (31st-40th time) of operation the concentration of ethanol from the treated waste-air at each sampling port was raised again and the removal efficiency decreased to *ca.* 60%. At the 4th stage (41st-50th time) of operation the operating temperature of the biofilter was reset back to 30 °C to confirm the recurrence of the concentration profiles of the 1st stage of operation. As a result, the concentration profile of ethanol of the 4th stage of operation at each sampling port was almost consistent with that of the 1st stage of operation. At the 5th stage (51st-54th time) the operating temperature of the biofilter was increased to 40 °C so that the concentration of ethanol from treated waste-air at each sampling port was higher than that at any other stage of operation of the experiment and the removal efficiency was reduced to less than 60%.

Time-evolution of elimination capacity versus inlet load is shown as in Fig. 5. At the 1st half of the 1st stage of operation the elimination capacity of ethanol was *ca.* 160 g/m^3/h, as in Fig. 5, which should be the sum of the capacities of adsorption as well as biodegradation. However the elimination capacity of ethanol was *ca.* 130 g/m^3/h at the 2nd half of the 1st stage of operation, when adsorption was saturated and only biodegradation contributes to the elimination capacity. Thus, the elimination capacities of *ca.* 30 g/m^3/h and 130 g/m^3/h resulted from the adsorption capacity of the media at 30 °C packed in the biofilter and the biodegradation capacity at 30 °C, respectively. As in Fig. 5 the elimination capacities of the 2nd (25 °C) and the 3rd (35 °C) stages of operation decreased to 120 and 100 g/m^3/h, respectively, after the packing media of the biofilter was saturated by adsorption. Thus, upon saturation of the packing media by adsorption each elimination capacity corresponded to the bio-

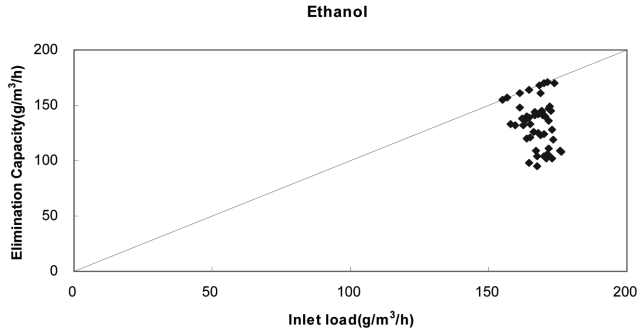

Fig. 6. Elimination capacity (g/m^3/h) versus inlet load of ethanol at the exit of a biofilter.

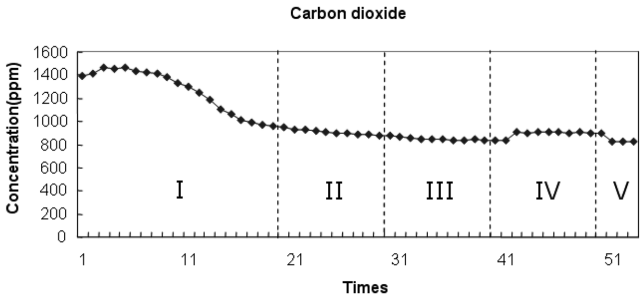

Fig. 7. Time evolution of carbon dioxide generation.

degradation capacity at each given temperature. In the same way the biodegradation capacity was increased to 140 g/m^3/h at the 4th stage (30 °C) of operation and decreased to below 100 g/m^3/h at 5th stage (40 °C) of operation.

The elimination capacity of this experiment turned out to range between *ca*. 90 g/m^3/h and 160 g/m^3/h with the inlet load of 155-175 g/m^3/h (theoretical inlet load of 158.26 g/m^3/h from Table 1) as in Fig. 6. The experimental data of elimination capacity were distributed vertically as in Fig. 6 within the range of the fore-said inlet load. Above 130 g/m^3/h of elimination capacity from Fig. 6 the experimental data may be interpreted as obtained at 30 °C before the packing media of the biofilter was saturated by adsorption. The experimental data below 130 g/m^3/h of elimination capacity from Fig. 6 were obtained from 2nd, 3rd and 5th stages of operation. Carbon dioxide generated from the biofilter is shown as in Fig. 7, where its concentration increased a little bit between 1st time and 5th time, which may be regarded as adaptation period of microbes, rapidly decreased prior to 15th time and then smoothly reached the condition of steady-state at the end of 1st stage of operation. The rapid decrement of the CO_2 concentration may be interpreted as that a carbon source more favorable to *Pseudomonas putida* (KCTC1768) was provided to, and was accumulated in, the biofilter during the period of recycling of liquid medium containing dissolved nutrient broth (Merck) for the inoculation of the microbes like the work of Lim and Park [2004] before the accumulated-more-favorable carbon source was consumed rapidly, since the recycling of the liquid medium stopped and the operation of biofiltration started. It was observed that the transient behavior of CO_2 generation from Fig. 7 was in a similar pattern to that of biodegradation capacity as in Table 3. Hence the optimum operating temperature for the performance of the

Table 3. Biodegradation capacity of each stage of biofilter-operation

Description \ Stage (times)	I (1-20)	II (21-30)	III (31-40)	IV (41-50)	V (51-54)
Biodegradation capacity (g/m^3/h)	130 (30 °C)	120 (25 °C)	100 (35 °C)	140 (30 °C)	95 (40 °C)

biofilter inoculated with *Pseudomonas putida* (KCTC1768) turned out to be 30 °C from the experiments. However, the optimum incubation-temperature of *Pseudomonas putida* (KCTC1768) was obtained to be 25 °C when the microbes were incubated in the same liquid medium as in the work of Lim and Park [2004] at the temperature ranged from 20 °C to 40 °C [Lim and Park, unpublished data], which is consistent with the optimum incubation-temperatures of *Pseudomonas putida* (KCTC1768) and the equivalent (i.e., NCIMB8858) of 26 °C and 25 °C announced by Korea Collection for Type Cultures (KCTC) and National Collections of Industrial, Food and Marine Bacteria (NCIMB), respectively [Jones and Turner, 1973]. Thus, the optimum operating temperature for the performance of the biofilter inoculated with *Pseudomonas putida* (KCTC1768) turned out to be higher than its optimum incubation temperature by *ca*. 5 °C.

CONCLUSIONS

The removal efficiencies (or elimination capacities) of the five consecutive temperature-stages of operation were measured and were compared with each other so that the optimum operating temperature of a biofilter turned out to be *ca.* 30 °C, which was consistent with the experimental result of Lim and Park [2004]. However the optimum incubation-temperature of *Pseudomonas putida* (KCTC1768) was obtained to be 25 °C when the microbes were incubated in the same liquid medium as in the work of Lim and Park [2004] at the temperature ranged from 20 °C to 40 °C [Lim and Park, unpublished data]. Moreover the optimum incubation-temperatures of *Pseudomonas putida* (KCTC1768) and the equivalent (i.e., NCIMB8858) were announced to be 26 °C and 25 °C by Korea Collection for Type Cultures (KCTC) and National Collections of Industrial, Food and Marine Bacteria (NCIMB), respectively [Jones and Turner, 1973]. Thus the optimum operating temperature of the biofilter inoculated with *Pseudomonas putida* (KCTC1768) was proved to be 30 °C, which was higher than its optimum incubation-temperature by *ca*. 5 °C.

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