Simultaneous observations of moisture behavior and gaseous VOCs removal in a biofiltration system

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Abstract Relationship between moisture behavior and removal efficiency of gaseous VOCs (volatile organic compounds) with packed tower type biofiltration has not been investigated enough. In this research, holding amount of nutrients, the amount of moisture evaporation, toluene and MEK (methyl ethyl ketone) gas removal were observed simultaneously in a biofiltration in which porous synthetic resin was used as the packing material. Holding amount of nutrient in one of the reactor is higher than other two ones, due to frequent supply of nutrient solution with the process of soaking of the packing layer. This reactor exhibited highest toluene gas removal, however, excess biomass growth was also observed. Another reactor, which was operated with less frequency of nutrient solution supply by soaking, showed a little less removal of toluene, possibly because of the lack of nutrient holding in the packing layer. One more reactor was operated with spraying of the nutrient solution to the packing layer as the common method of moisture supply, and the lowest toluene gas removal was obtained, mainly because of uneven nutrient supply. Moreover, evaporation ratio of moisture in the packing layer during the moisture supply interval was calculated, and heat balance was also evaluated.

Keywords: Biofiltration, gaseous VOCs, Moisture supply, Heat balance

1. Introduction

Biofiltration, biological technologies for air pollution control, have been emerged for past three decades as an off-gas treatment method. It is regarded as an environmental friendly and economical method than conventional physical/chemical treatment methods (Estrada, 2015). To sustain high removal efficiency by biofilters, parameters such as water content, inlet air relative humidity, temperature, pH, and nutrient concentration should be controlled (Klapkova, 2006).

Microbial activity is hugely dependent on the amount of moisture present in the filter bed of biofiltration, (Detchanamurthy, 2012). Therefore, maintaining appropriate amount of moisture in packing material is a major concern for its effectiveness. A critical aspect of biofilter operation is the control of moisture content of the bed material (Sun, 2002).

Lack of moisture leads to drying of the filter bed, and it derives airflow channeling by the development of cracks/fissures (Mudilar, 2010), or other types of irreversible damage to the packing material occurs (Beuger, 2009). Also, insufficient moisture results in low growth of microorganisms, and it leads the system into performance reduction (Armeen, 2008).

Excess water in filter bed can cause a formation of anaerobic zones, compaction and clogging, which becomes a barrier of transport of oxygen and hydrophobic VOCs to biofilm and limits the reaction rate (Cheng, 2016).

Optimal water levels vary with different packing material, depending on surface area, porosity and other factors. Moisture content for optimal operation of the biofiltration should be within 30-60% by weight (Mudilar, 2010). The recommended water content is commonly evaluated at 50% of the water-holding capacity of the material (Malhautier, 2005). Moisture control in biofiltration requires a better understanding of the drying of packing material due to change in inlet air temperature, relative humidity and from production of metabolic heat during pollutant oxidation.

Some researchers have proposed novel design of biofiltration systems, and the authors also showed a new system, SFMC (Switch-Feed Multi-Column biofilter)(Morita, 2012). The main characteristic of SFMC is equipping with changing gas flow direction to grow microorganisms in the filter bed evenly. And another unique function is that entire filter bed is soaked in liquids containing nutrients as irrigation to deliver complete watering and nutrient supply throughout the filter bed.

In this study, holding amounts of moisture and nutrients by packing material of a biofiltration system were observed continuously. And simultaneously with these observations, removal of gaseous toluene and MEK were also monitored. The relationship between the behavior of moisture and the removal of target gases were discussed based on these results. Especially, water and heat balance were evaluated, and influences of these values on the removal of target gases were considered. Such results were obtained from two kinds of reactors in which different kinds of irrigation, soaking and spraying, were conducted, and the observed results were compared between them.

2. Materials and Methods

2.1. Experimental Setup

In this experiment, air which was contaminated by VOCs was treated by three reactors, packed-column type biofilter. Diameter and packing height of a reactor were 0.1m and 0.3m, respectively. Gaseous VOCs which contain toluene and MEK was generated from the liquid mixture of toluene–MEK placed in VOC gas generator, was diluted by room air, and was flowed into the reactors. Supplying nutrient solution for two reactors was carried out by soaking method imitating SFMC. In the remaining one, the nutrient solution was supplied by spraying method as done by usual biofiltration. The schematic diagram of the experimental setup is shown in Figure 1.

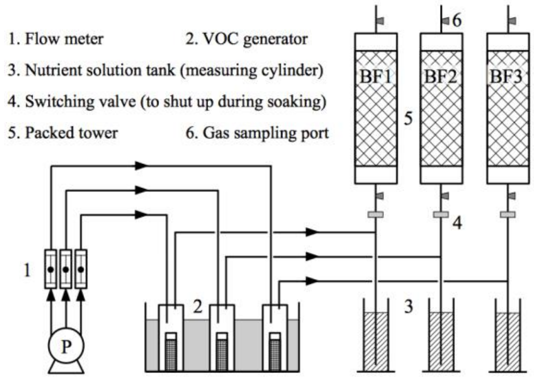

Figure 1. Experimental setup of biofiltration

2.2. Packing Material

In the experiments, the reactors were filled with the packing material, porous PVF (Polyvinyl formal) carrier [Be-Fine LL prototype, AION Co., Ltd]. Figure 2 shows the shape and physical properties of this packing material, respectively.

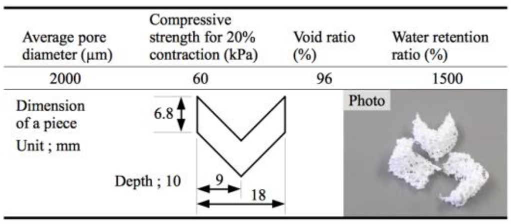

Figure 2. Specification of the packing material

2.3. Operating Conditions

In the experiment, three reactors (BF1, BF2, and BF3) were operated with unique irrigation conditions given for each reactor. Operating conditions and the composition of nutrient solution for irrigation are shown in Table 1 and Table 2, respectively. Acclimation was subjected to all reactors for 10 days with twice a week of the frequency of irrigation for all the reactors. For both of irrigation methods, soaking and spraying, nutrient solution was flowed from the top of the filter bed using a commercially available watering pot. 5 min was spent for both soaking and spraying to the reactor, and drainage was collected back to a 3 L measuring cylinder for measuring the volume of liquid and repeatedly used for irrigation. The nutrient solution was prepared any time, and it was added to the drainage at the amount equal to the loss.

Table 1. Operating conditions of biofiltration

		BF1	BF2	BF3
Time / period	(day)	1-46	1-46	1-46
Irrigation method		soaking	soaking	spraying
Frequency of irrigation	(times/week)	2	1	2
Average inlet gas temperature	(°C)	21.0	20.7	20.7
Flow rate	($L\ min^{-1}$)	5	5	5
Residence time	(sec)	28.8	28.8	28.8
Average inlet toluene concentration	(ppm)	38.8	42.8	44.0
Average inlet MEK concentration	(ppm)	57.4	55.8	67.2
Average inlet load of toluene	($g\ m^{-3}h^{-1}$)	16.5	20.5	19.2
Average inlet load of MEK	($g\ m^{-3}h^{-1}$)	20.5	20.9	25.8

Table 2. Composition of nutrient solution for irrigation

Nutrient components	$mg\ L^{-1}$
KNO_3	4000
NH_4Cl	2100
$Na_2HPO_4 \cdot 12H_2O$	7200
KH_2PO_4	2700
$MgSO_47H_2O$	2100
$CaCl_2 \cdot 2H_2O$	170
$ZnSO_4 \cdot 7H_2O$	8
$Na_2Mo_4 \cdot 2H_2O$	43
$CoCl_2 \cdot 6H_2O$	65
$MnCl_2 \cdot 4H_2O$	670
$FeSO_4 \cdot 7H_2O$	73

2.4. Measurement Methods

A gas mixture of toluene and MEK were collected from sampling port provided in inlet and outlet of each reactor with a 1.0 ml syringe [Ito micro syringe, Ito Seisakusho Co., Ltd., Japan]. Sampling was conducted both before and after irrigation, but the sampling for after irrigation was done at 15 minutes after finishing the irrigation.

Toluene and MEK in the gas samples were measured by gas chromatograph with FID detector [GC-2014, Shimadzu, Japan], and a wide-bore capillary column [G-300, Chemicals Evaluation and Research Institute, Japan] for VOCs measurement was equipped. Helium as the carrier gas flowed at a flow rate of 20 ml min-1 and the column temperature was set at 50 °C.

Temperature and humidity measurements of the air flow in both inlet and outlet of the reactors were measured at the same ports as used for gas sampling by a thermo-recorder [Thermo Recorder RS-12, Espec Mic Corp., Japan]. The frequency of these measurements was a time a day. However, as the same manner as gas sampling, these measurements were done at both before and after the irrigation in a day when the irrigation was carried out. For the purpose of acquiring stable results, the values by thermo-recorder were read after 5 minutes from the time of inserting sensor of the recorder and starting the measurement. Humidity measurement was also carried out using a gas tube detector in parallel once a week with the Thermo Recorder [No.177SA, Komyo rikagaku kogyo Corp.].

3. Resuts and Discussion

Moisture balance of each reactor is shown in Table 3. It was considered that more amount of nutrient components had been transferring to the packing layer than expected by the multiplication of two values, moisture transfer amount and the concentration of nutrient. Despite the nutrient supply was carried out by the same method (soaking), BF2 has a higher water evaporation rate than BF1 and BF3. The reason why the moisture evaporation rate of BF1 is lower than that of BF2 is that the water holding amount in BF1 itself was maintained high due to frequent supply of nutrient solution (twice a week). It was thought that moisture was retained by overgrowth of microorganisms and such a situation was remarkable for BF1. Regarding BF3, although based on visual observation, the packing material was sufficiently dried within the period of irrigation. There is the possibility that the frequency of moisture measurement, a time a day, was not enough to evaluate moisture balance, because of too low values in the ratio of evaporation to retention. It may be necessary to carry out the more frequent humidity measurement, such as every several hours.

VOCs removal in the results of experiment was summarized in Figure 3. BF1 removed toluene almost completely, whereas a certain amount of remaining toluene was observed in outlets of BF2, and BF3. Drying of the packing layer by fewer frequency of irrigation and uneven distribution of moisture and nutrient components in the packing layer derived from the spraying irrigation were possible reasons for insufficient toluene removal in BF2 and BF3, respectively. MEK gas was removed more than toluene generally, however, the comparison of three reactors was similar to the case of toluene removal.

Table 3. Moisture balance of each reactor

		BF1	BF2	BF3
Time / period	(day)	4-46	4-46	4-46
Cummulative moisture	(mL)	1973	1401	1128
Cummulative moisture retention	(mL)	3420	1640	1950
Evaporation ratio	(%)	58	85	58

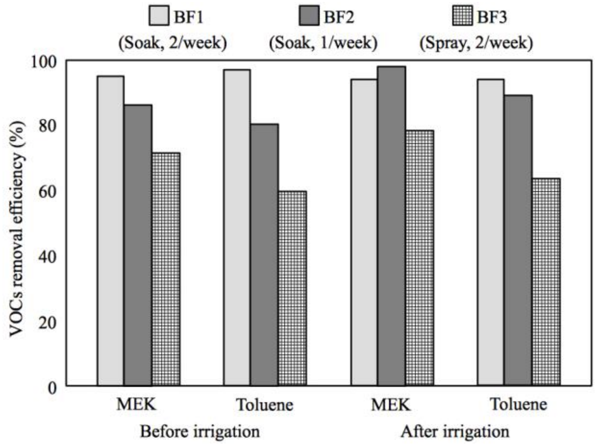

Figure 3. Results summary of gaseous VOCs removal

Based upon VOCs gas removal and moisture evaporation, heat generation in each reactor was estimated. Results of the heat balance based on the following formula are shown in Table 4. Negative values were obtained as a whole in this experiment, it shows that the heat loss due to evaporation of water is larger than the heat production by VOC decomposition. This value approached to zero only before irrigation in BF3. As a practical matter, the negative value of the heat must be larger than these values, due to energy usage by microbial growth which was not estimated in this experiment.

$$Es = Ed - Em - Ee$$

Where:

Es: Accumulation of heat in paking layer

Ed: Heat production by VOCs decomposition

Em: Heat transfer from packing layer to air flow

Ee: Heat consumption by moisture evaporation

These results suggest that the dominant driving force for water evaporation was not the heat by VOC decomposition, but the humidity difference between the packing layer and the gas phase. Therefore, at least in a similar operating condition of VOCs removal by biofiltration, humidity control of the air flow plays a very important role for controlling moisture of the packing layer.

Table 4. Heat balance of each reactor

Values in kJ day^{-1}

	BF1	BF2	BF3
Time / period	4-46	4-46	4-46
Heat acummulation before irrigation	-44.2	-22.7	-4.7
Heat acummulation after irrigation	-48.2	-25.9	-24.6

4. Conclusions

In this study, comparison of moisture behavior and comparison of gas removal efficiency by different irrigation methods, the soaking/spraying methods, as well frequency of irrigation were conducted. Within the range of the operating conditions in this study, The performance of gaseous VOCs removal was highest in the reactor of which frequent and soaking irrigation was conducted, probably due to enough supply of both moisture and nutrients. However, in this reactor (BF1), moisture evaporation rate was low and excessive microorganisms overgrowth was observed in the packing layer. In condition of fewer frequency of irrigation (BF2), moisture evaporation ratio was increased but VOCs removal was decreased. Soaking irrigation had advantages more than spraying irrigation in both gaseous VOCs removal and moisture supply. Under the conditions of this experiment, heat consumption due to moisture evaporation was superior to the heat generation by VOCs decomposition. Observing moisture more minutely by taking more frequent measurement is indispensable to establish appropriate methods for moisture control in biofiltration.

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