Chemical Engineering Journal 137 (2008) 198–204

Chemical Engineering Journal

www.elsevier.com/locate/cej

Operational parameters in biofiltration of ammonia-contaminated air streams using compost–pieces of hard plastics filter media

H. Taghipour [a,*], M.R. Shahmansoury [b], B. Bina [b], H. Movahdian [b]

[a] *Department of Environmental Health Engineering, Tabriz University of Medical Sciences, Tabriz, Iran*

[b] *Department of Environmental Health Engineering, Isfahan University of Medical Sciences, Isfahan, Iran*

Received 7 June 2006; received in revised form 1 November 2006; accepted 9 April 2007

Abstract

This study evaluates the use of a mixture of compost, sludge and pieces of hard plastics as a biofilter medium to remove ammonia from a waste gas stream through a bench-scale biofilter column. This study investigated the effects of operational parameters such as inlet concentration, loading rate, retention time, pressure drop and variations of pH and alkalinity in the packing material on the performance of the biofilter. After a start-up period with an average inlet concentration of ammonia of about 51 ppm_v corresponding to a loading rate of 2.15 g NH_3/m^3 h and an empty bed residence time of 60 s, the biofilter reached a removal efficiency of more than 97.9% by day 10. The maximum elimination capacity of 9.85 g NH_3/m^3 h was achieved at a loading rate of 9.86 g NH_3/m^3 h, corresponding to an inlet concentration of about 236 ppm_v, with the outlet concentration of NH_3 increasing for higher inlet concentrations. The pH and alkalinity of the bed medium decreased due to nitrate formation but there was no need to control them synthetically. The concentration of ammonium and nitrate in the bed medium decreased and increased, respectively. Under steady-state conditions, the number of nitrifying bacteria increased from an initial 5.6×10^4 cell/g wet material in the bed medium to about 2.8×10^8 cell/g wet material. Biological removal and nitrification were the dominant processes in ammonia removal. The maximum pressure drop during the experiment was 12 mm H_2O for each meter of column. The minimum retention time that the system could attain at an average loading rate of $\leq$9.45 g NH_3/m^3 h was 30 s.

Keywords: Biofiltration; Ammonia; Compost; Operating parameters

1. Introduction

Ammonia is emitted into the atmosphere from farmed livestock, the petrochemical industry, oil refineries, metal manufacturing, food, pulp and paper industries, textile plants, wastewater treatment plants and composting plants [1,2]. Ammonia is a colorless, toxic, reactive and corrosive gas with a very sharp odor. Ammonia vapor is an irritant to the eyes and the respiratory tract, and acute exposure to high concentrations can lead to death within minutes [3–5]. This emission, in addition to its own toxicity, constitutes a source of olfactory nuisance [5]. The traditional methods for treatment of ammonia are based on physical and/or chemical processes, such as adsorption on activated carbon, wet scrubbing and condensation, which are generally expensive and produce secondary waste that may require further treatment or disposal, thereby creating additional environmental problems [1,3,7].

Recently, biological processes have received much attention as an alternative for treatment of polluted air [8]. The principle of biofiltration is relatively simple; a contaminated air stream is passed through a porous packed bed on which pollutant-degrading cultures of microorganisms are immobilized [9]. As the odorous and contaminated air passes through the bed, the contaminants in the air stream are absorbed by the biofilm, and then these contaminants are oxidized to produce biomass, CO_2, H_2O, $NO_3{}^-$ and $SO_4{}^{-2}$. Biofiltration is an emerging technology that offers a number of advantages over traditional methods of air pollution control for the treatment of low-concentration polluted air streams. Besides its highly efficient removal of pollutants, low capital expenditure and operating costs, safe operating conditions and low energy consumption, it does not generate undesirable byproducts and it converts many organic and inor-

* Corresponding author. Tel.: +98 411 3357580; fax: +98 411 3340634.
E-mail address: hteir@yahoo.com (H. Taghipour).

1385-8947/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.cej.2007.04.015

ganic compounds into harmless oxidation products [10,11]. Also simplicity of design has been cited as a reason for the popularity of biofilters [12].

Biofiltration of ammonia-laden waste gas streams has been studied by a number of researchers. The packing material for the column has included inorganic packing material inoculated with the newly isolated marine bacterium *Vibrio alginolyticus* [8], peat and peat seeded with nitrifying bacteria and a mixture of compost and activated carbon [13], ceramic, granulated and calcinated soil [14], woodchips [10], zeolite and oyster shells [15]. However, a mixture of compost, municipal activated sludge and shredded hard plastics has rarely been used as a packing material for biofiltration of ammonia. The selection of packing materials and inoculated microorganisms has a decisive effect on biofiltration operation [15]. Quality indicators include microbial density, porosity, moisture content, pH, surface area, pressure drop and cost. Compost has been used widely for biofilter media because of its low cost, high nutrient content and ease of availability. Negative aspects include the development of back-pressure due to gradual compaction with time, and aging effects due to microbial mineralization [15,16].

In this bench-scale study municipal activated sludge was used to cultivate compost medium without an enrichment process to enhance the microbial density and improve the homogeneity of the packing material. The reactor was packed with yard waste compost-based medium mixed with shredded hard plastics as the bulking agent for reducing the pressure drop. The objectives of this study were: (a) estimation of the acclimation period of a biofilter inoculated by activated sludge for degradation of ammonia; (b) evaluation of the operational parameters of the system; (c) determination of the effectiveness of a new packing material for the biological degradation of ammonia.

2. Materials and methods

2.1. Biofilter set-up

A three-stage, bench-scale downward biofilter constructed from a cylindrical metal container with an effective overall height of 129 cm and an internal diameter of 8 cm was used in this study (Fig. 1). The column stages were separated by perforated plates that acted as a support for the packing material as well as for gas redistribution. Provision of sampling ports at the up stage, mid stage and down stage allowed access to the bed medium. A 7 cm space between the sections allowed gas sampling from the inlet and the outlet of each layer.

Compressed air was passed through a column of granular activated carbon to retain residual oil and particles, and then sparged through a 16 l water container equipped with a heated element for adjusting the temperature and humidification of the gas stream. Changing the water temperature in the humidifier allowed control of the humidity of the inlet gas stream and the biofilter material. A synthetic polluted gas stream was prepared by injecting a controlled amount of pure ammonia from a gas cylinder equipped with a precision gas regulator (Herice Co.). The overall air stream flow through the column was measured with a gas flow-meter (Platon Co.). A digital thermometer was

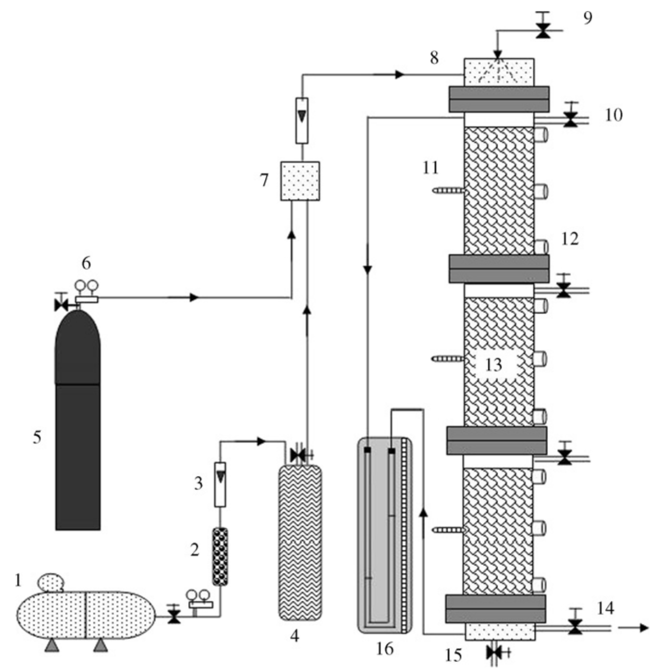

Fig. 1. Schematics of the biofilter system: 1, compressor; 2, carbon filter; 3, flow meter; 4, humidifier; 5, ammonia gas cylinder; 6, regulator; 7, mixing chamber; 8, inlet; 9, water inlet; 10, gas sampling port; 11, thermometer; 12, sampling port; 13, biofilter bed; 14, outlet; 15, leachate; 16, manometer.

used to keep the temperature of the bed material at 30(±1) °C, which is the optimum temperature for the growth and activity of nitrifying bacteria [17], by using a heating tape wrapped around the exterior of the reactor wall. This prevented environmental temperature effects and any disturbance of the steady-state conditions of the biofilter. The water content of the bed was maintained at 40–65% during the study period. Monitoring the pressure drop along the column bed was conducted with a glass U-type water manometer.

The bed medium was prepared by mixing yard waste compost (Isfahan Compost Co.) with shredded high-density plastics (1.0 cm × 0.5 cm) as a bulking agent to increase the porosity of the bed material, and thickened activated sludge at a ratio of 3:2:1 (v/v/v) with a porosity of 52%, a density of 0.65 and a pH of 7.2. In preparing the packing medium, thickened activated sludge was obtained from a municipal wastewater treatment plant (Isfahan Water & Wastewater Co.) with the aim of adding to the microbial density, improving the homogeneity of the compost particles and its adhesion to the bulking agent.

2.2. Analytical methods

Concentration of ammonia in the gas samples was determined by a colorimetric indophenol method [18]. Gas sampling ports were connected to an impinger containing a solution of sulfuric acid to trap ammonia gas. To investigate the transformation of ammonia in the reactor, a 5 g solid sample were taken from the three sampling ports, then the nitrogen from ammonium (NH_4^+-N), and the nitrogen from nitrate (NO_3^--N) were analyzed using standard methods [19]. The water content of the bed material was measured by drying a known amount of the bed material at 105 °C for about 24 h, and the reduction in mass was considered as the moisture of the bed [20]. To determine the pH and alkalinity value of the medium, 50 ml of distilled water was added to a 5 g sample and blended to be used for measurement [13,20]. The cell number of nitrifying bacteria was estimated by the most probable number (MPN) method. About 5 g wet weight of the packing material was sampled and homogenized in 95 ml of Alexander (AL) medium at 10,000 rpm for 10 min. AL medium contained 2.5 g $(NH_4)_2SO_4$, 0.5 g KH_2PO_4, 50 mg $MgSO_4·7H_2O$, 4 mg $CaCl_2·2H_2O$ and 0.1 mg Fe-EDTA per liter, at pH 8.0–8.2. The homogenized suspension was diluted with AL medium, then 0.5 ml of the suspended solution with different dilution ratios was transferred to 4.5 ml of AL medium in 18 cm tubes, and incubated in the dark for 3 weeks at 30 °C at 120 spm. At the end of the incubation, each tube was scored by adding 2.2 g diphenylamine in 100 ml concentrated H_2SO_4 to test for the presence of nitrate and or nitrite. The development of a blue color indicated that nitrite and nitrate were formed, and the tube was scored positive. By referring to the MPN table, the positive number was used to estimate the population cell number [8].

3. Results and discussion

3.1. Acclimation time

After inoculation of the biofilter with thickened municipal activated sludge, the system was operated with an airflow rate (Q) of 0.388 m^3/h corresponding to an empty bed residence time (EBRT) of 60 s with an average inlet loading (L) rate of 2.15 g NH_3/m^3 h. Frequent increases and decreases were observed in the removal efficiency of ammonia during the first days of operation, and the system showed a completely unstable condition (Fig. 2). Then the removal efficiency of the biofilter increased gradually and reached about 97.9% on day 10; the system became stable after that. Also according to Fig. 4 the concentration of ammonium in the packing material, except on the first day of operation, decreased and the concentration of nitrate increased gradually in the three stages of the biofilter during the acclimation time. So, it was concluded that after 10 days of acclimation,

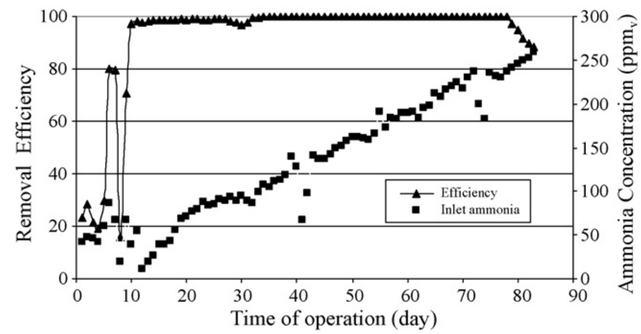

Fig. 2. Overall performance of compost bed biofilter in removal of ammonia.

the nitrifying microorganisms and biological removal process became dominant. Smet and Langeenhove [21] observed no microbiological start-up period in the case of the treatment of highly concentrated ammonia-loaded waste gas in a compost-based biofilter. Malhautier et al. [6] used granulated sludge as the packing material in biofiltration of air loaded with a mixture of ammonia and hydrogen sulfide, and reported an acclimation period of 7 weeks for nitrifying microorganisms. Liang et al. [13] reported 2 weeks as the acclimation time for biotreatment of ammonia with a compost-based biofilter with activated carbon added (Table 1). Comparison of these results, except the first one, indicates that the acclimation period in this study was less, and it was concluded that inoculation of the biofilter medium with aggregates like thickened municipal activated sludge can reduce the acclimation time. This is consistent with the results reported for biofiltration of other pollutants [16,22,23].

3.2. The elimination capacity

The removal efficiency (RE) as a function of time is shown in Fig. 2, and the relationship between elimination capacity (EC) and ammonia loading rate is presented in Fig. 3. After the acclimation period and reaching steady-state condition in the biofilter with flow-rate (Q) of 0.388 m^3/h yielding an EBRT of 60 s, the inlet concentration and loading rate were increased gradually. During this period, the elimination capacity and removal efficiency increased, and the maximum EC of 9.85 g NH_3/m^3 h (RE 99.9%) was achieved at loading rate of 9.86 g NH_3/m^3 h,

Table 1
Comparison of overall performance of biofilter with other research studies

Authors	Bed media	Acclimation time (day)	EC	RE (%)	EBRT (s)	Pressure drop (Pa/m)
This study	Compost, sludge, hard plastics	10	9.85 g NH_3/m^3 h, 9.44 g NH_3/m^3 h	99.9, 99.9	60, ≥30	36.98, –
Pinnette et al. [24]	Compost, bark mulch, wood chips	–	1 g NH_3/m^3 h	–	–	–
Yani et al. [27]	Peat and night soil sludge	–	3.24 g N/kg-dry peat-day	93.1	32	–
Liang et al. [13]	Compost and activated carbon	15	0.02–0.391 g NH_3/kg-media-day	95–99.6	31.9–79	–
Kapahi and Gross [25]	Compost, oyster shells and perlite	–	10.6 g NH_3/m^3 h	96.4	–	–
Pagans et al. [28]	Compost	No start-up due to high absorption	0.829–21.7 g NH_3/m^3 h	46.7–98.8	86	725
Baquerizo et al. [29]	Coconut fiber	15	11.47 g NH_3/m^3 h	86.2–100	36	–

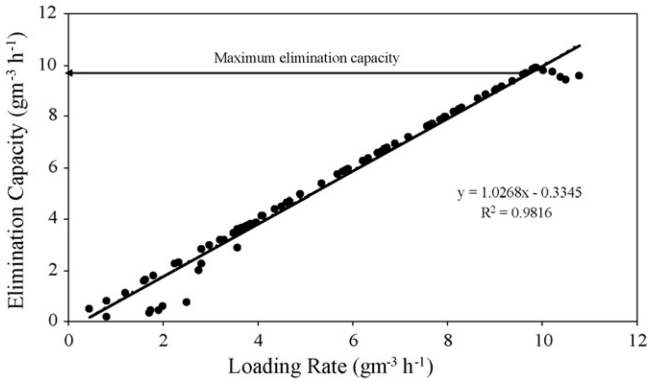

Fig. 3. Relationship between elimination capacity and loading rate of ammonia.

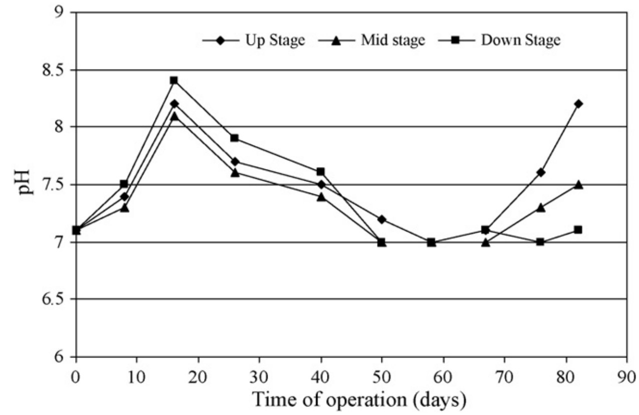

Fig. 5. Change of pH in the medium of biofilter.

corresponding to an inlet concentration of about 236 ppm_v. The concentration of ammonia in the effluent was less than 1 ppm_v (the emission standard) [13]. But the concentration of NH_3 at the outlet and the elimination capacity were increased and decreased, respectively, for higher inlet concentrations and the system became unstable due to reaching concentrations of ammonia and loading rates above the inhibition limit. It was concluded that the loading rate should be less than 9.86 g NH_3/m^3 h (236 ppm_v for the concentration of ammonia) to achieve a good long-term performance. Liang et al. [13] used a compost-based biofilter with activated carbon as an added material at inlet concentrations of ammonia of 20 ppm_v and 500 ppm_v and achieved an EC of 0.02–0.391 g NH_3/kg medium per day. Pinnette et al. [24] reported that in a biofilter with a mixture of compost, bark mulch and wood chips as the packing material reached an EC of 1 g NH_3/m^3 h and Kapahi and Gross [25] used a mixture of compost, oyster shell and perlite as a biofilter medium and reported an EC equivalent to 10.6 g NH_3/m^3 h (Table 1).

3.3. *Various forms of nitrogen in the medium, and pH and alkalinity changes*

The concentrations of ammonium and nitrate in the medium at different points of the biofilter are shown in Fig. 4. The pH and alkalinity are shown in Figs. 5 and 6, respectively. The con-

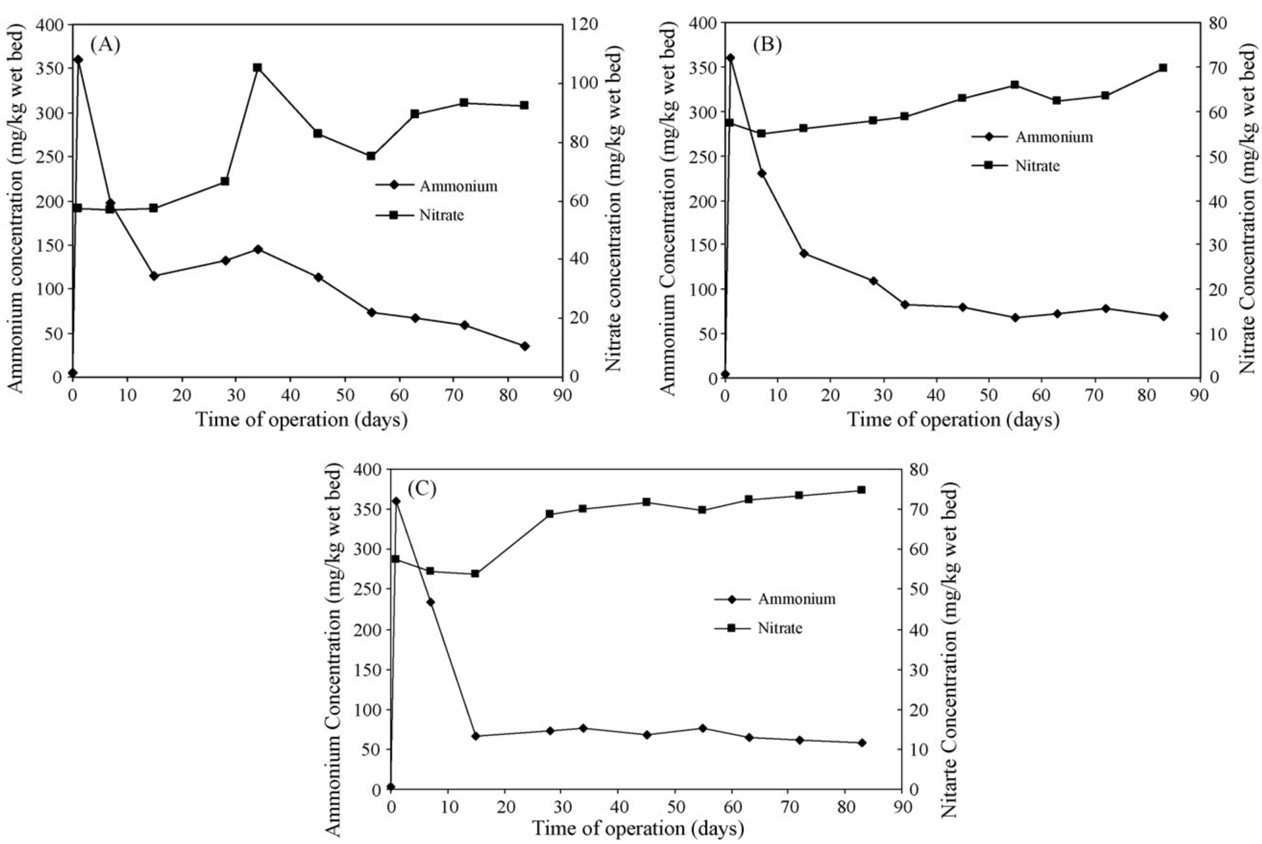

Fig. 4. Concentration changes of ammonium and nitrate in the medium of different stages of biofilter. (A) Up stage, (B) mid stage and (C) down stage.

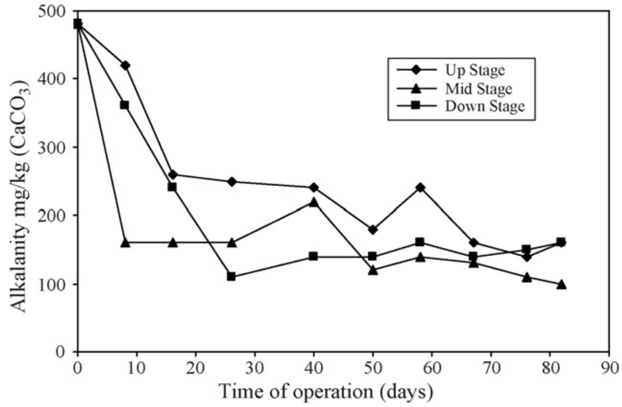

Fig. 6. Change in alkalinity concentration in medium of biofilter.

centration of ammonium in the medium before start-up was 3–5 mg/kg wet bed. On the first day of operation the concentration of ammonium increased rapidly to about 360 mg/kg wet bed. This increase is related to absorption of the highly soluble ammonia in the packing material; after that, the concentration of ammonium decreased during the whole period of operation of the biofilter. According to Fig. 4, the concentration of nitrate was about 57 mg/kg wet bed at the beginning of biofiltration, increased gradually in the first 2 weeks in all three parts of the biofilter, and then increased rapidly in all parts until day 79. There was a reduction in the concentration of nitrate in the first stage of the biofilter on day 50 and again on day 60; these were attributed to washing of nitrate from the packing material. It can be seen that the ammonia absorbed by the filter bed was ultimately converted to nitrate by nitrifying microorganisms after the acclimation period. At the same time, the total alkalinity of the packing medium decreased from the initial value of 480 mg/kg wet bed ($CaCo_3$) to 160 mg/kg wet bed, 100 mg/kg wet bed and 160 mg/kg wet bed ($CaCo_3$) at the sampling ports in the up stage, mid stage and down stage, respectively. The reduction of alkalinity in medium was due to nitrification process. Evaluation of variations in the levels of ammonium, nitrate and alkalinity at different sampling ports in the column revealed that the rate of reduction of the concentration of ammonium and alkalinity were faster in the third stage of the reactor column (80–129 cm). These results imply that the third stage of the biofilter, especially in the first month of operation, was the most active layer for the removal of ammonia. It was concluded that the small amount of ammonia-oxidizing and nitrite-oxidizing biomass leaching from the upper stages (0–40 and 40–80 cm) probably had a seeding role for the nitrifying bacteria in the third stage of the biofilter. This is not in accord with another study, in which the first stage was reported to be the most efficient part of the biofilter [13]. As shown in Fig. 6, the initial pH value of the packing material was about 7.2, and with the increasing concentration of ammonia injected reached pH values of about 8.2, 8.1 and 8.4 in the three stages on day 16. This was unexpected, because, the pH value should be reduced due to oxidation of ammonia and nitrate production. It was conclude that due to the predominance of unstable conditions on the biofilter at the beginning of biofiltration, the ammonia absorbed by the bed caused the increase of pH. This is in agreement with the results obtained by Kim et al. [8] for biofiltration of high concentrations of ammonia. Then pH value decreased gradually and reached about 7 in all stages of the biofilter, this may be caused by nitrate accumulation in the biofilter. Then, in the last days of operation of the biofilter, the pH increased again, which was due to unstable conditions in the biofilter. The detection of ammonia gas at the outlet corresponded to the increase in pH value of the bed medium. The investigation of variation of alkalinity and pH indicated that in this study there was no necessity to control pH or alkalinity in the biofilter synthetically. Hirai et al. [14] reported that in ammonia biofiltration with inorganic packing materials, control of pH in the bed medium was achieved with an alkaline solution, such as $NaHCO_3$. According to this result, it can be concluded that the mixture of compost, shredded hard plastics and thickened municipal activated sludge had a greater ability to maintain a neutral pH and provided a suitable environment for nitrifying bacteria than inorganic packing materials.

3.4. Microbial count

The initial number of nitrifying bacteria in the packing material was about 5.6×10^4 cell/g wet material. After, start-up and an acclimation period under steady-state conditions, the number of these bacteria increased to about 2.8×10^8 cell/g wet material. Although the MPN method is only a statistical estimation of the numbers of bacteria, the cell numbers of bacteria in the medium in stable conditions was 5000 times greater than the initial number. This can be explained by the fact that in the reactor of the biofilter, the nitrifying bacteria became dominant under steady-state conditions.

3.5. Column pressure drop

Resistance to gas flow is the major factor that determines the amount of energy needed by the blowers to force the contaminated gas through the filter [7]. In the course of our experiment, the pressure drop was monitored continuously with a water manometer and plotted as a function of time. As shown in Fig. 7, the system had some pressure drop that might be related to the moisture content of the bed medium. The average pressure drop was 3.77 mm H_2O or 36.98 Pa in each meter of the column,

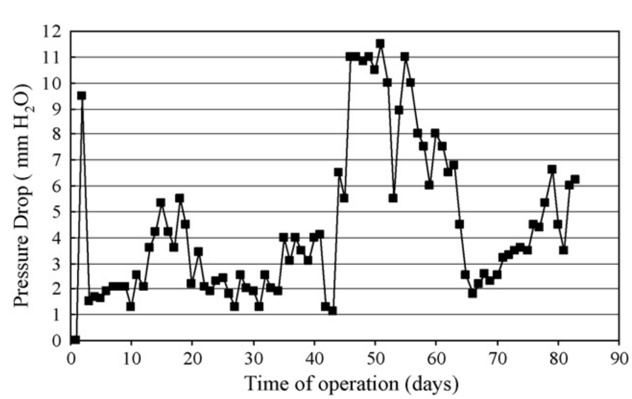

Fig. 7. Pressure drop in biofliter column (with 129 cm effective heigth).

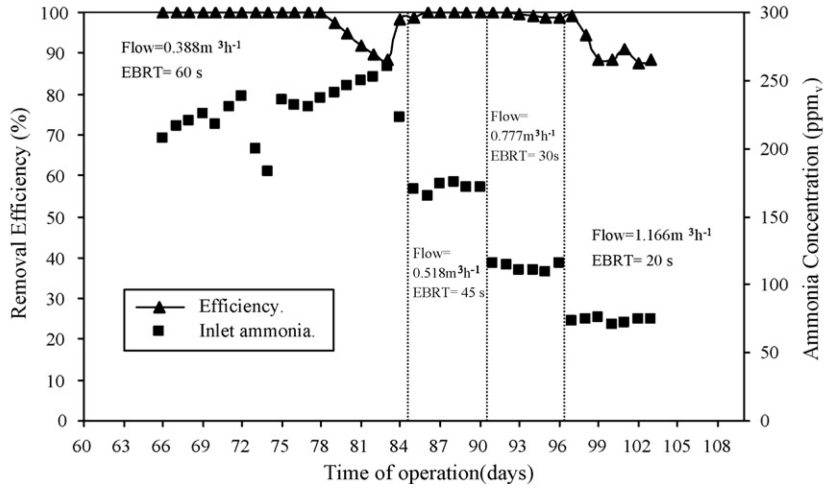

Fig. 8. Biofilter performance at different flow-rates and EBRTs.

which is less than pressure drop of 28–128 Pa in each meter reported for a biofilter with wood chips as the bulk medium [10] and the 218 Pa/m reported for compost-based biofilter [17]. These results imply that using compost in the mixture with thickened municipal activated sludge and shredded hard plastics is a suitable biofilter medium for removal of ammonia from waste gas streams and has only a low drop of pressure.

3.6. Performance of the biofilter with different EBRTs

One of the major objectives of this research was to investigate the response of a biofilter to substantial perturbations of effluent characteristics. Therefore, the experiment was conducted in three phases based on the inlet gas flow-rate. The results are shown in Fig. 8. The first phase began on day 85 and finished on day 91. The gas flow-rate in this phase was 0.518 m^3/h, and the average inlet concentration was about 170 ppm_v, yielding an EBRT for the contaminated air stream of 45 s and a loading rate of 9.48 g NH_3/m^3 h. In the second phase on day 91, the flow-rate was increased to 0.777 m^3/h and the inlet concentration was decreased to about 113 ppm_v corresponding to an EBRT of 30 s and a loading rate of 9.40 g NH_3/m^3 h. In all of these stages, concentration of ammonia in the effluent was less than 1 ppm_v. The last phase of the experiment commenced on day 97; the flow-rate was increased to 1.166 m^3/h, thereby reducing the EBRT to 20 s, and the inlet concentration was reduced to about 76 ppm_v and the loading rate reached 9.49 g NH_3/m^3 h. In this phase, as shown in Fig. 8, especially in the last days of operation, the RE and the outlet concentration of ammonia decreased and increased, respectively. The system began to be unstable due to reduction of EBRT and raising the ammonia load above the inhibition limit. According to the results of this experiment at EBRTs of 60, 45 and 30 s for the average $L \leq 9.45$ g NH_3/m^3 h, the elimination capacity remained very close to 9.44 g NH_3/m^3 h (RE = 99.9%). At an EBRT of 20 s, the EC and RE decreased and the average reached about 8.52 g NH_3/m^3 h and 91%, respectively. It was concluded that in the biofiltration system utilized in this study, the shortest EBRT that the system could attain was 30 s. Liang et al. [13] reported a shortest EBRT of 32 s for removal of ammonia in a compost-based biofilter with activated carbon as an added material, which is consistent with the present study. Demeestere et al. [26] achieved a minimum EBRT of 21 s, corresponding to 12.5 g NH_3/m^3 h, in a biofilter with compost as the packing material (Table 1). Back-pressure along the biofilter column did not change dramatically with increasing flow-rates and loading rates, due to the high porosity of the bed material. The maximum pressure drop of 12 mm H_2O for each meter of the biofilter column was observed at a flow-rate of 1.166 m^3/h.

4. Conclusion

- An acclimation period of about 10 days for degradation of ammonia in a biofilter achieved an average loading rate of 2.15 g NH_3/m^3 h, and an EBRT of 60 s. The biofilter medium with thickened municipal activated sludge reduced the acclimation time greatly.
- A maximum EC of 9.85 g NH_3/m^3 h was achieved at an EBRT of 60 s at a loading rate of 9.86 g NH_3/m^3, corresponding to an inlet concentration of ammonia of about 236 ppm_v, with an average RE of more than 99.9%.
- Maximum and average pressure drop were obtained 12 mm H_2O and 3.77 mm H_2O for each meter across the biofilter bed. Using a mixture of shredded high-density plastics as a bulking agent can reduce the pressure drop, due to a high level of porosity in the bed.
- Reduction of pH and alkalinity in the packing material due to accumulation of nitrate on the bed medium, increasing number of nitrifying bacteria (5000 times) and, finally, reduction of the concentration of ammonium in the column medium indicated the predominance of biological removal of ammonia under steady-state conditions.
- In the biofiltration used in this study, the shortest EBRT could attain was 30 s for $L \leq 9.45$ g NH_3/m^3 h.

Acknowledgement

Funding for this work was provided by the Isfahan University of Medical Sciences.

References

[1] W.T. Davis, Air Pollution Engineering Manual, second ed., Wiley/ Interscience Publication, 2000.

[2] G. Busca, C. Piostarino, Abatement of ammonia and amines from waste gases, a summary, J. Loss Prev. Process Ind. 16 (2003) 157–163.

[3] US EPA, Control and pollution prevention options for ammonia emissions, EPA-456/R-95-002, 1995.

[4] Ontario Ministry of the Environment, Ontario Air Standards for Ammonia, Ontario, 2001.

[5] Y.C. Chung, C. Huang, C.P. Tseng, J.R. Pan, Biotreatment of H_2S and NH_3 containing waste gases by co-immobilized cells biofilter, J. Chemosphere 41 (2000) 329–336.

[6] L. Malhautier, C. Grecian, J.C. Roux, J.L. Fanlo, P.l. Cloirec, Biological treatment process of loaded with an ammonia and hydrogen sulfide mixture, Chemosphere 50 (2003) 145–153.

[7] R.J. Abumaizar, W. Kocher, E.H. Smith, Biofiltration of BTEX contaminated air streams using compost-activated carbon filter media, J. Hazard. Mater. 60 (1998) 111–126.

[8] N.-J. Kim, Y. Sugano, M. Hirai, M. Shoda, Removal of a high load of ammonia gas by a marine bacterium, *Vibrio alginolyticus*, J. Biosci. Bioeng. 90 (2000) 410–415.

[9] M.A. Deshusses, H.H.J. Cox, Biotrickling Filters for Air Pollution Control, Department of Chemical and Environmental Engineering University of California.

[10] B.A. Sheridan, T.P. Curran, V.A. Dodd, Assessment of the influence of media particle size on the biofiltration of odorous exhaust ventilation air from a piggery facility, Bioresour. Technol. 84 (2002) 129–143.

[11] J.S. Devinny, M.A. Deshusses, T.S. Webster, Biofilteration for Air Pollution Control, Lewis Publishers, 1999.

[12] M. Zilli, E. Palazzi, L. Sene, A. Converti, M. Del Borghi, Toluene and styrene removal from air in biofilter, Process Biochem. 37 (2001) 423–429.

[13] Y. Liang, X. Quan, J. Chen, J.S. Chung, J.Y. Sung, S. Chen, D. Xue, Y. Zhung, Long-term results of ammonia removal and transformation by biofiltration, J. Hazard. Mater. B80 (2000) 259–269.

[14] M. Hirai, M. Kamamoto, M. Yani, M. Shoda, Comparison of the biological NH_3 removal characteristics among four inorganic packing materials, J. Biosci. Bioeng. 91 (4) (2001) 428–430.

[15] D. MacNevin, J. Barford, Biofiltration as an odour abatement strategy, Biochem. Eng. J. 5 (2000) 231–242.

[16] R. Dehganzadeh, A. Torkian, B. Bina, H. Poormogaddas, A. Kalantary, Biodegradition of styrene laden waste gas stream using compost-based biofilter, Chemosphere 60 (2005) 434–439.

[17] G. Bitton, Wastewater Microbiology, Wiley-Liss, 1994.

[18] L. Lodge, P. James, Methods of Air Sampling and Analysis, third ed., Lewis Publisher Inc., 1990.

[19] Agriculture Ministry of Iran, Chemical Analysis Methods of Soil, No. 1024, 1996.

[20] APHA, Standard Method for the Examination of Water and Wastewater, 18th ed., American Public Health Association, Washington, DC, 1992.

[21] E. Smet, H. Langeenhove, Abetment of high concentrated ammonia loaded waste gases in compost biofilter, Water Air Pollut. 119 (2000) 177–190.

[22] M.E. Acuna, F. Perez, R. Auria, S. Revah, Microbiological kinetic aspects of biofilter for the removal of toluene from waste gases, Biotechnol. Bioeng. 63 (1999) 175–184.

[23] H. Jorio, L. Bibeau, M. Heitz, Biofiltration of air contaminated by styrene: effect of nitrogen supply flow rate, and inlet concentration, Env. Sci. Technol. 34 (2000) 1764–1771.

[24] J.R. Pinnette, M.D. Giggey, G.J. Marcy, M.A.O. Brie, Performance of biofilter at tow agitated bin facilities, in: Proceeding of the 87th Annual Meeting of Air and Waste Management Association, Air and Waste Management Association, Ohio, 1994.

[25] R. Kapahi, M. Gross, Biofiltration for VOC and ammonia emission control, BioCycle 36 (2) (1995) 87–90.

[26] K. Demeestere, H.V. Langeenhove, E. Smet, Regeneration of a compost biofilter degrading high loads of ammonia by addition of gaseous methanol, Air Waste Manage. Assoc. 52 (2002) 796–804.

[27] M. Yani, M. Hirai, M. Shoda, Removal kinetics of ammonia by peat biofilter seeded with night soil sludge, J. Ferment. Bioeng. 85 (5) (1998) 502–506.

[28] E. Pagans, X. Font, A. Sánchez, Biofiltration for ammonia removal from composting exhaust gases, Chem. Eng. J. 113 (2–3) (2005) 105–110.

[29] G. Baquerizo, J.P. Maestre, T. Sakuma, M.A. Deshusses, X. Gamisans, D. Gabriel, J. Lafuente, A detailed model of a biofilter for ammonia removal: model parameters analysis and model validation, Chem. Eng. J. 113 (2–3) (2005) 205–214.