

Evaluation of aerated biofilter systems for microbial methane oxidation of poor landfill gas

R. Haubrichs^{*}, R. Widmann

University of Duisburg-Essen, Department of Waste Management and Waste Technologies, Universitaetsstrasse 15, 45141 Essen, Germany

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Abstract

In the long-term, landfills are producing landfill gas (LFG) with low calorific values. Therefore, the utilization of LFG in combined heat and power plants (CHP) is limited to a certain period of time. A feasible method for LFG treatment is microbial CH_4 oxidation. Different materials were tested in actively aerated lab-scale bio-filter systems with a volume of 0.167 m^3 . The required oxygen for the microbial CH_4 oxidation was provided through perforated probes, which distributed ambient air into the filter material. Three air input levels were installed along the height of the filter, each of them adjusted to a particular flow rate. During the tests, stable degradation rates of around $28 \text{ g}/(\text{m}^3\text{h})$ in a fine-grained compost material were observed at a CH_4 inlet concentration of 30% over a period of 148 days. Compared with passive (not aerated) tests, the CH_4 oxidation rate increased by a factor of 5.5. Therefore, the enhancement of active aeration on the microbial CH_4 oxidation was confirmed. At a O_2/CH_4 ratio of 2.5, nearly 100% of the CH_4 load was decomposed. By lowering the ratio from 2.5 to 2, the efficiency fell to values from 88% to 92%. By varying the distribution to the three air input levels, the CH_4 oxidation process was spread more evenly over the filter volume.

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1. Introduction

CH_4 is second to CO_2 in contributing to global warming, and CH_4 absorbs and reradiates 23 times the energy of CO_2 over an observation period of 100 years. Landfills are regarded to be a major source of anthropogenic CH_4 (IPCC, 2001). In Europe, an estimated 30% of anthropogenic CH_4 emissions are from the waste sector (EEA, 2001). In 1990, the landfills in Germany accounted for approximately 29% (1399 Gg CH_4) of the German atmospheric input. As a result of changes in the environmental laws, site closing and improvements in waste technologies, the CH_4 emissions from landfills in Germany decreased to about 20% (498 Gg CH_4) in 2001 (UBA, 2003). Through the use of proper measures, like active degasification, the CH_4 -emissions from landfills can be controlled up to a coverage of about 80–90%, depending on the boundary conditions of each landfill and its gas collection and control

system. The utilization of rich landfill gas (LFG) with a CH_4 content above 45% in combined heat and power (CHP) plants is the most reasonable state-of-the art treatment method. It offers the possibility to substitute fossil fuels and to obtain an additional revenue by feeding the produced electricity into the grid. In Germany, the law for renewable energies (EEG, 2000) guarantees the price stability for electricity production from LFG.

However, the production and the composition of LFG are varying over time. In the long run, the CH_4 content and the total amount of produced CH_4 are decreasing. The time-dependent behavior of the gas production is intimately connected to the chemical and biological processes during the degradation of organic compounds in the landfill (Christensen et al., 1996). Below a CH_4 content of about 35–40% in the LFG and a total LFG production of about 30–50 m^3/h , the treatment in CHP plants becomes technically and economically unsuitable. This is the reason why the use of LFG for heat and power production is limited to a certain period of time. In Germany, the LFG treatment is compulsorily prescribed by law regardless of the CH_4

^{*} Corresponding author. Tel.: +49 201 183 2743; fax: +49 201 183 3465.
E-mail address: roland.haubrichs@uni-essen.de (R. Haubrichs).

content or the total amount of CH₄ (TASi, 1993; AbfAbIV, 2001). These days, with decreasing CH₄ values, the proper treatment of the LFG is warranted by high temperature flares. This treatment method is momentarily available down to about 20–25% CH₄ content and about 10–15 m³/h of total LFG production. Below these values the treatment of poor LFG becomes more expensive, using methods like fluidized bed combustion or catalytic oxidation. The period of time with poor LFG production is estimated to last much longer than the one with beneficial gas utilization. Therefore, the need for inexpensive and easy-to-care techniques for LFG treatment becomes more and more important.

An economical and ecologically applicable way for poor LFG treatment is the biological CH₄ oxidation by methanotrophic bacteria. Related to landfills, they are present in cover liners, where CH₄ emissions occur in a wide range of flux rates (Bogner et al., 1997). As O₂ availability is limiting CH₄ oxidation, a system that enhances O₂ availability in the substrate will enhance CH₄ oxidation (Barlaz et al., 2004). A major enhancement in the O₂-supply compared to passive systems like landfill biocovers are actively aerated biofilter systems, which provide optimum CH₄ oxidation conditions all over the filter material. Aerated biofilter systems are only reasonable at landfills with a gas collecting system, where the LFG is used in CHP or treated in high temperature flares at the moment. Biocovers can be applied in the absence of a gas collecting system or as a polishing step in addition to an active system (Barlaz et al., 2004).

In investigations on biofilter systems for CH₄ oxidation by Streese and Stegmann (2003), the LFG was mixed with air in the input of the filter to provide sufficient oxygen concentrations inside the material. The CH₄ concentration in the LFG was thinned to values between 0.2% and 2.5%. This was done to ensure a CH₄ concentration below 50% of the lower explosive limit (LEL) of methane. Therefore, the biofilter system is run with excess air related to the required amount of air for complete bacterial CH₄ oxidation. By monitoring the O₂ concentration in the LFG, a biofilter system can even be operated with CH₄ concentrations between 5% and 15% (LEL–UEL). In the presented tests, the required air for CH₄ oxidation is injected directly into the filter material at three levels. As a result, the size of the filter should be smaller and the efficiency for bacterial CH₄ oxidation should be increased.

The aim of this paper is to describe the results from tests with active aerated biofilter systems for poor gas treatment from older landfills, where the utilization and the flaring of the LFG is no longer feasible.

2. Materials and methods

2.1. Testing setup

The experiments were conducted in three lab-scale biofilter columns at increasing technical LFG flow. All columns were made of stainless steel, were used in former

investigations by Felske (2003) concerning CH₄ oxidation in passive landfill biocover systems, and were modified for the new tests. The columns had a diameter of 50 cm, two had a height of 1.5 m and one 2.0 m. Before the filter material was emplaced, the gastightness of the columns was verified with water and compressed air at 2.0 bar. At the start of the tests each filter contained 167 l filter material above a 20 cm thick gas distribution layer out of 16/32 filter gravel.

The technical LFG with 30/70 CH₄/CO₂ was moisturized and fed into the bottom of the filter column. The filter was operated in up-flow mode to separate the clean gas output from the leachate water outlet at the bottom of each column. The up-flow mode should also prevent the accumulation of CH₄ in the headspace of the column (density of CH₄ ≈ 0.6 relative to air). The feed gas flow could be controlled by two rotameters, one for CH₄ and one for CO₂. Three ambient air input levels along the height of the biofilter were installed for sufficient air supply. At every input level the ambient air was moisturized and the flow rate was controlled by a rotameter. Two perforated probes (10 mm diameter) distributed the adjusted air flow rate at each level into the filter substrate. The total air flow was divided to 1/2, 1/3 and 1/6 to the three air input levels from bottom to top to take the declining CH₄ concentrations along the column into account. The consumption of 2 mol O₂ per mol CH₄ for complete oxidation of CH₄ was used as a simplified assumption. The total oxygen flow rate was calculated at 2.5 times the CH₄ flow rate including a safety margin of 25%. By assuming that no microbial degradation and no production of CH₄ occur inside the filter material, the decreasing CH₄ concentrations are caused by the ambient air input. With an inlet concentration of 30% CH₄, the concentration of CH₄ is decreasing to 10.8% in air input level 1, to 7.6% in level 2 and to 6.6% in level 3, as well as in the clean gas (Table 3). The ratio between CH₄, CO₂ and air input is kept constant during the whole testing period. This is why the calculated concentrations of CH₄ inside the column are independent from the fluxes. A flow chart of the filter system and a top view of an air distribution level are given in Fig. 1.

The temperatures in the filter substrate were monitored using PT 100 sensors in four levels along the height of the column. The temperatures were continuously logged into a computer. The concentrations of CH₄, carbon dioxide and oxygen were recorded in the gas input, at four depths inside the substrate and in the exhaust using a GA 94 (CH₄ and CO₂ measured with infrared-spectroscopy, O₂ measured with galvanic cell) from Geotechnical Instruments. The gas flow rate in the exhaust was quantified using a mass-flow meter. The operational data of the four filter tests is included in Table 1. All tests were conducted at room temperature.

2.2. Biofilter materials

Four different filter materials were tested. In earlier passive system tests, a compost substrate showed sufficient

Table 2
Characteristics of the used filter materials

Parameter	Paper pellets	Compost	Wood chips
Ignition loss (%)	86.7	32.2	92.5
Conductivity ($\mu\text{S}/\text{cm}$)	922	1600	232
TOC (%)	38.3	21.3	34.9
C/N (–)	111.2	13.7	28.4
$\text{NH}_4\text{-N}$ (mg/l)	0.3	3.4	0.1
$\text{NO}_3\text{-N}$ (mg/l)	4.3	41.5	6.2
pH (–)	7.8	7.2	6.6
AT_4 (mg O_2/g) ^a	15.7	1.9	7.1
Bulk density (kg/m^3) ^b	345.2	645.9	386.2
Water content (start) (%) ^b	50.0 ($\pm 0.5\%$)	50.0 ($\pm 0.5\%$)	50.0 ($\pm 0.5\%$)

^a Related to dry mass.

^b Related to moist mass.

or anaerobic processes take place inside the biofilter system, the concentrations of CH_4 , CO_2 and O_2 can be calculated (Table 4).

The specific filter efficiency depends on the CH_4 load of the filter. This is why the efficiency is plotted over time with the associated CH_4 load. The CH_4 degradation rate can be calculated with $D_r = e_f q_{m,\text{in}}$, where $q_{m,\text{in}}$ is the CH_4 input flow rate in $\text{g}/(\text{m}^3\text{h})$. In the calculations, a mean conversion factor of $718.0 \text{ g}/\text{m}^3 \text{ CH}_4$ is used (Weast, 1985).

3. Results and discussion

3.1. Influence of increasing gas flow rates

During the tests the flow rates of LFG and thus the CH_4 load of the biofilter system was increased stepwise. At every step the flow rates of LFG and ambient air were kept constant for about 20 days until stable conditions and a CH_4 degradation of nearly 100% was observed.

3.1.1. Compost material

After the first 34 days with a CH_4 load of $5.1 \text{ g}/(\text{m}^3\text{h})$ the air supply was switched on. Already after 65 days of operation (31 days with air supply) and a CH_4 load of $6.8 \text{ g}/(\text{m}^3\text{h})$ the CH_4 degradation efficiency fell from nearly 100% to values of 32%. During these days the color of the material shifted from dark to light brown, which was observed through windows in the column. Therefore, drying out of the material was assumed. In the following 12 days the filter material was slowly moisturized with the built-in sprinkling system. From day 91 the CH_4 specific degradation efficiency was re-established to nearly 100%. During the drying of the material and the moisturizing phase, the CH_4 load was kept constant. After nearly 100% CH_4 oxidation was reached, again the CH_4 load was stepwise increased to $28.8 \text{ g}/(\text{m}^3\text{h})$ on day 223. Between day 223 and day 240 the CH_4 oxidation remained at nearly 100%. The value chart of the CH_4 load and the CH_4 oxidation efficiency is shown in Fig. 2.

On day 105 exopolymeric substances (EPS) were visible through windows in the column for the first time. The EPS was surveyed in the lower part of the filter, especially at the border between gas distribution layer and compost. At this time the efficiency of the CH_4 oxidation has not been influenced strongly from the observed EPS. EPS production is frequently associated with CH_4 oxidation and may lead to declining CH_4 degradation rates because of pore clogging and thus reduced permeability (Hilger et al., 1999; Humer and Lechner, 1997). Wilshusen et al. (2004) stated that no convincing information is available in the literature regarding why EPS is produced or what conditions are required to prevent its formation. They found less EPS production at an O_2 concentration of 1.5% than at 10.5%. It was assumed that EPS is produced by type I methanotrophs, as a carbon cycling mechanism in the case of inor-

Table 3
Dilution of CH_4 and CO_2 by air input (e.g., $40 \text{ l}/(\text{m}^3\text{h})$ CH_4 filter load)

	ΔQ_{air} (l/h)	$\Delta Q_{\text{CH}_4^a}$ (l/h)	$\Delta Q_{\text{CO}_2^a}$ (l/h)	Q_{sum} (l/h)	CH_4 (%)	CO_2 (%)	O_2 (%)
Clean gas output	0	0	0	101.74	6.57	15.32	16.41
Level 4 (950)	0	0	0	101.74	6.57	15.32	16.41
Level 3 (700)	13.25	0	0	101.74	6.57	15.32	16.41
Level 2 (450)	26.49	0	0	88.49	7.55	17.61	15.72
Level 1 (200)	39.74	0	0	62.00	10.77	25.13	13.46
LFG input	0	6.68	15.58	22.26	30.00	70.00	0

^a Assumption: no CH_4 or CO_2 degradation or production inside the filter.

Table 4
Calculated concentrations of CH_4 , CO_2 and O_2 (e.g., $40 \text{ l}/(\text{m}^3\text{h})$ CH_4 filter load)

	$Q_{\text{CH}_4^a}$ (l/h)	$Q_{\text{CO}_2^a}$ (l/h)	Q_{O_2} (l/h)	Q_{N_2} (l/h)	Q_{sum} (l/h)	CH_4 (%)	CO_2 (%)	O_2 (%)
Clean gas output	0	21.14	3.35	62.79	87.28	0	24.22	3.84
Level 4 (950)	0	21.14	3.35	62.79	87.28	0	24.22	3.84
Level 3 (700)	1.11	20.03	5.57	62.79	89.50	1.24	22.24	6.22
Level 2 (450)	3.34	18.92	7.23	52.32	81.81	4.08	23.13	8.84
Level 1 (200)	6.68	15.58	8.35	31.39	62.00	10.80	25.13	13.47
LFG input	6.68	15.58	0	0	22.26	30.00	70.00	0

^a Assumption: only CH_4 oxidation takes place, no digestion or composting of organic material.

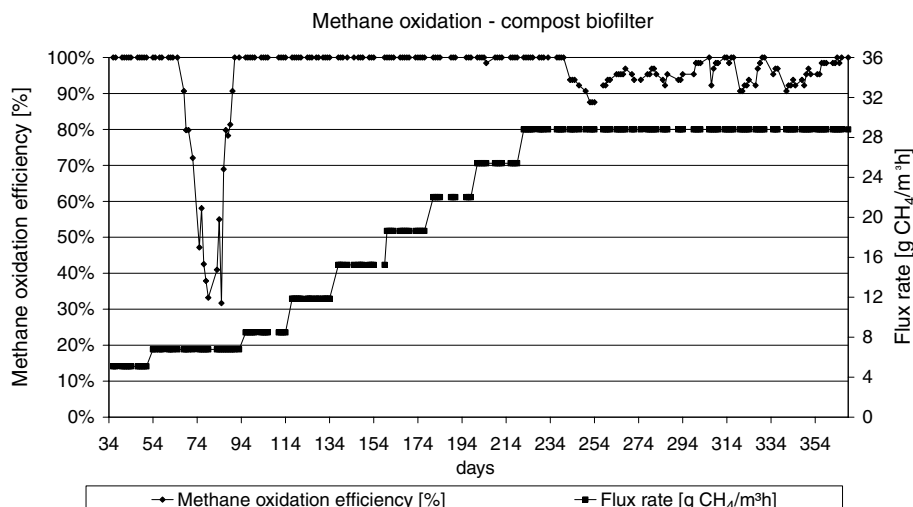


Fig. 2. CH_4 load and CH_4 oxidation efficiency over time (compost).

ganic nitrogen limitation. It is hypothesized that the increasing CH_4 load and a O_2 concentration more than 8% all over the filter leads to increasing EPS production and the EPS becomes visible. This could be a hint to avoid excess air and thus higher O_2 concentrations than 1.5% inside the biofilter system leading to less EPS production.

At 16 days after the maximum CH_4 load of 28.8 g CH_4 was reached, the filter efficiency fell to values about 95%. Assuming that the filter was drying out, the material was moisturized again. But this time no positive effect on the CH_4 oxidation efficiency could be observed. From day 240 till day 369 the efficiency remained at mean values of 96%.

As ambient air is introduced into the column at three levels, the calculated thinning of CH_4 and the measured CH_4 concentrations along the column are given in Fig. 3. Between the top of the gas distribution layer (200 mm)

and the third air input level (700 mm), the main part of the CH_4 oxidation takes place. This is indicated by the consumption of O_2 , and the production of CO_2 . At the highest area load of $28.8 \text{ g CH}_4/(\text{m}^3\text{h})$, the gas profile indicates CH_4 production in the lowest filter compartment due to low oxygen concentrations.

The corresponding average O_2 - and the CO_2 -profiles are shown in Fig. 4. The consumption of oxygen and the production of the carbon dioxide are a result of the aerobic CH_4 oxidation and aerobic composting processes of the filter material. With the installed measuring equipment the distinction between the two microbial processes is not possible. The average CO_2 profile reveals difficulties with the gas sampling inside the fine-grained compost. Although the CH_4 concentration in the clean gas output shows very low values, the CO_2 profile in the clean gas output fits, however, not to microbial activity. The profiles indicate

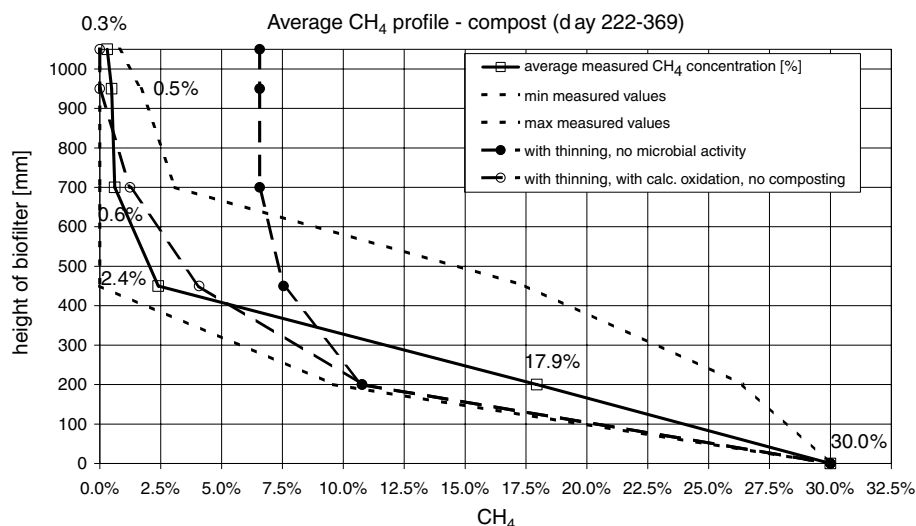


Fig. 3. Calculated thinning and average concentrations of CH_4 in the compost filter test, days 222–369 at $28.8 \text{ g CH}_4/(\text{m}^3\text{h})$.

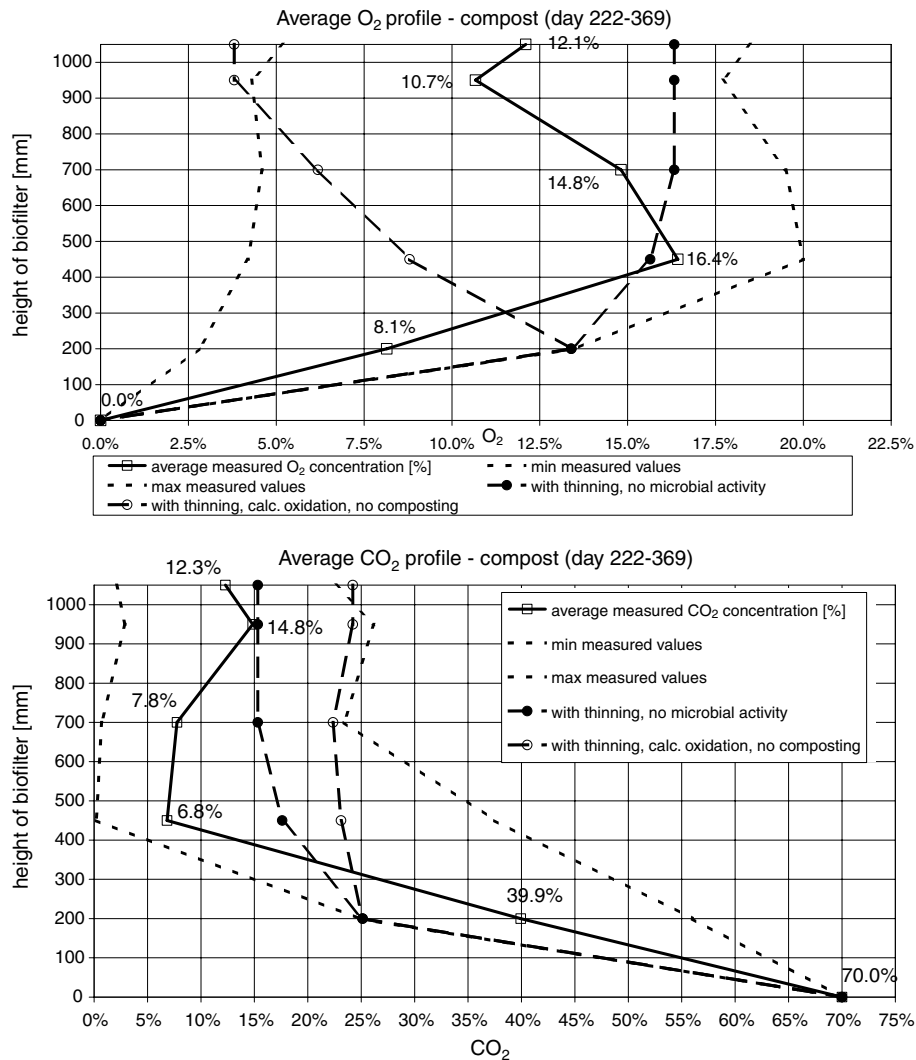


Fig. 4. Average O₂- and CO₂-profile in the compost filter test, days 222–369.

problems with sufficient gas mixing inside the compost material. The very widespread minimum and maximum values for CH₄, CO₂ and O₂ also support this observation.

3.1.2. Wood chips/compost mixture material

In contrast to the compost this material showed no major changes in the moisture content as the LFG flow rates were increased. For a period of more than 180 days and up to the maximum CH₄ load of 23.7 g/(m³h), the efficiency remained at nearly 100%. After the final CH₄ load had been reached, the filter efficiency fell to values about 90% (Fig. 5).

The mean gas profiles in the test with woodchips/compost mixture show more even values than in the compost test (Figs. 6 and 7). As the CH₄ and the CO₂ values at height 200 are higher than the calculated ones (with thinning and no microbial activity), anaerobic depletion of organic matter seems to be likely. The low corresponding O₂ value supports this assumption. In the middle and upper part of the filter the gas profiles show very similar

developing values compared to the calculated profile (with thinning, with CH₄ oxidation, no composting or digestion). The measured values of CH₄ and CO₂ seem to be shifted for the amount produced at height 200 by anaerobic processes. The low corresponding O₂ value seems to be caused by gas mixing problems.

3.2. Filter material temperatures

With increasing CH₄ load, rising temperatures inside the filter materials were observed. In the compost the temperatures reached values higher than 50 °C on day 212 and nearly 47 °C on day 174 in the wood chips/compost mixture. Due to higher gas flow rates in both tests, the zone with the highest temperatures moved slowly from bottom to top of the column. At this time the rising temperatures had no strong effect on the CH₄ efficiency of the whole filter. On day 124 a break in the LFG supply occurred due to problems with the gas delivery. During the following 20 h the highest temperature inside the filter fell from 43 to

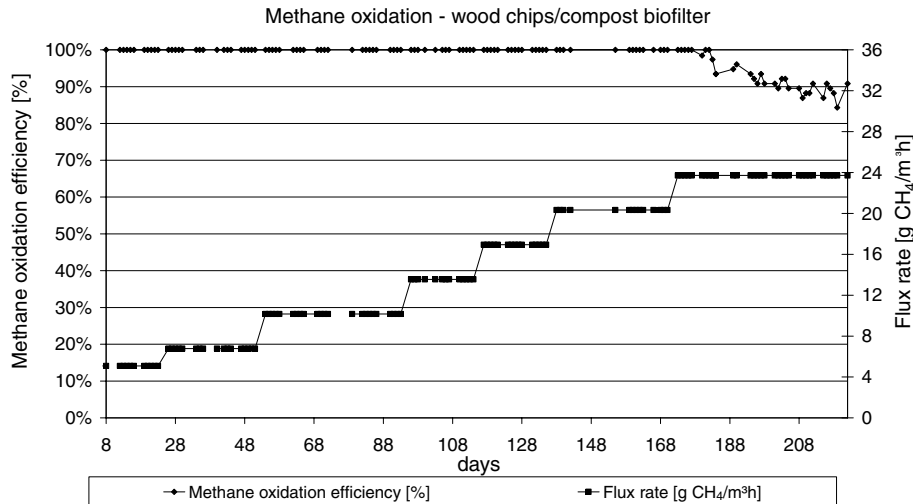


Fig. 5. CH_4 load and CH_4 oxidation efficiency over time (wood chips/compost).

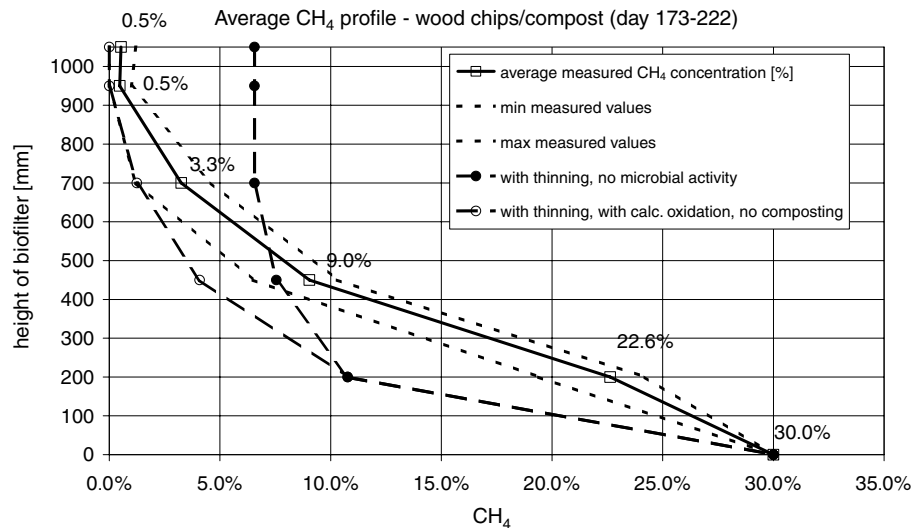


Fig. 6. Calculated thinning and average concentrations of CH_4 in the wood chips/compost filter test, days 173–222 at $23.7 \text{ g CH}_4/(\text{m}^3\text{h})$.

26°C (height 700) at an ambient temperature of 19°C . The air supply stayed in operation during the lack of technical LFG input. Considering the temperature drop it is assumed that very low aerobic composting occurs inside the filter and that the increasing temperatures were mainly caused by microbial CH_4 oxidation.

Decreasing temperatures in the lower part of the filters were assumed to be a result of the poor water solubility of CH_4 and O_2 and of the gas mixing problem in the lower part of the filter. With increasing gas flow speed the retention time was reduced. Hilger et al. (2000) observed that the production of EPS regulates CH_4 oxidation by constraining O_2 diffusion to cells embedded in the biofilm. Therefore, the CH_4 oxidation efficiency in the lower part of the filter decreased and the upper parts were more strongly activated.

3.3. Influence of variations in the air supply

In the test with the wood chips/compost mixture the air input was adjusted to a lower total input flow rate and to different distributions to the three air input levels. The CH_4 load was kept constant at $23.7 \text{ g}/(\text{m}^3\text{h})$ during the variations in the air supply.

The total oxygen input flux was lowered from a factor of 2.5 to 2 of the CH_4 flow rate on day 174. The goal was to reduce the gas flow speed and thus to re-activate the lower part of the filter for CH_4 oxidation. In the lowest air input level (level 1) the oxygen concentration dropped from 3.5–4.0% to 1.0–1.5%. The concentrations stayed nearly constant around 6.0% in level 2 and around 3.5% in level 3. Below the surface of the filter material (level 4, no air input), the oxygen concentration fell from 3.8% to values

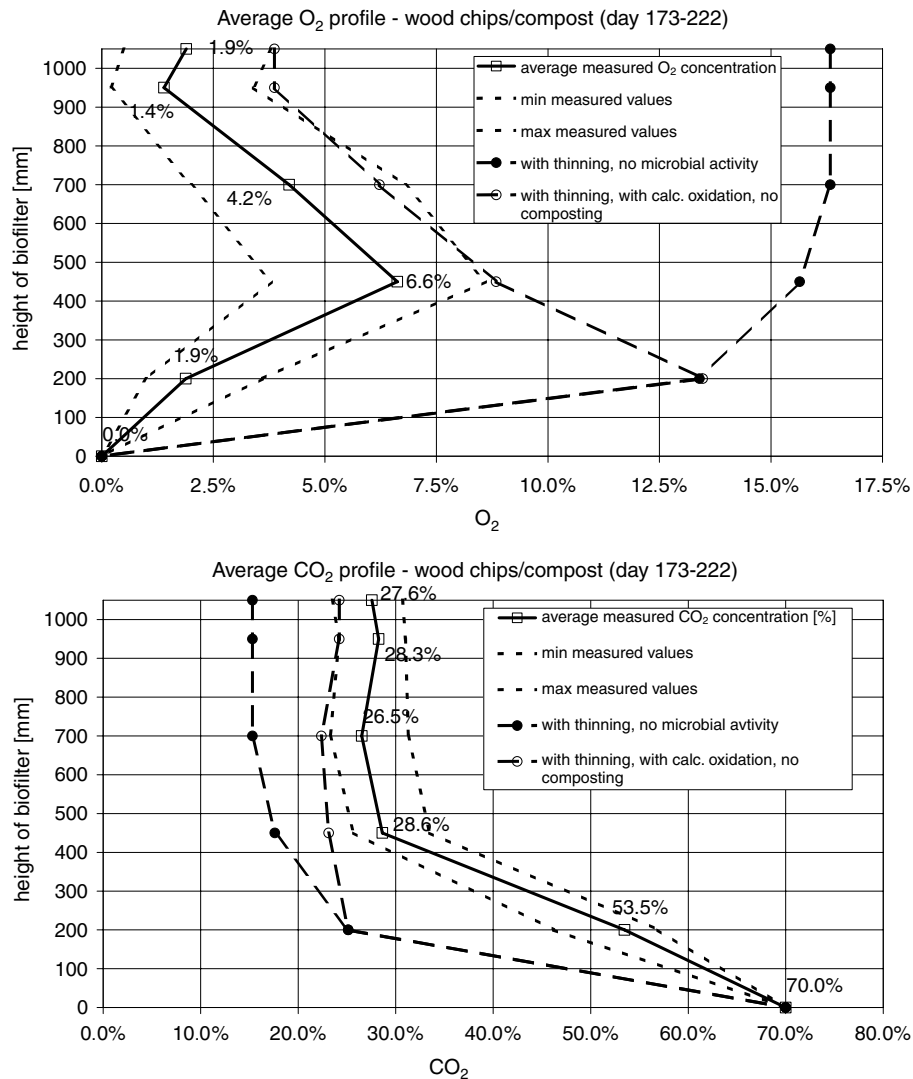


Fig. 7. Average O₂- and CO₂-profile in the wood chips/compost filter test, days 173–222.

below 2.5%. At the same time the oxidation efficiency of the whole filter decreased from nearly 100% to values about 90%.

After lowering the total air flow the distribution to the three air input levels were altered from 1/2, 1/3 and 1/6 (from bottom to top) to 1/2, 1/4 and 1/4 on day 204. The concentrations of oxygen did not change significantly in level 1 but rose from 6.0% to 7.6% in level 2 and from 4.0% to 5.4% in level 3. In level 4 the oxygen concentrations decreased from 2.4% to values of about 1.0%. By varying the air input distribution the CH₄ oxidation activity is spread more evenly over the height of the filter. Especially, the upper parts of the filter between 700 and 950 mm height are more activated, which is confirmed by the higher CO₂ production in this part of the filter. Despite the better utilization of the upper part of the filter, the CH₄ oxidation efficiency remained at values between 88% and 92%. Especially, the lower part of the filter stayed in anaerobic conditions with CH₄ and CO₂ production. Therefore, the

varied air distribution did not re-activate the lower part for CH₄ oxidation. It is hypothesized that the lower part is clogged by EPS production and saturated with water coming down from the CH₄ oxidation process in the upper parts of the filter.

3.4. Long-term filter performance

At the maximum CH₄ load of 28.8 g/(m³h), the compost filter test showed a mean CH₄ degradation rate of 28.5 g/(m³h) over 148 days with a minimum of 28.0 g/(m³h). The mean CH₄ oxidation efficiency during this period was calculated at 96.0%. In the wood chips/compost mixture, the maximum CH₄ load was 23.7 g/(m³h). This material showed a mean CH₄ degradation rate of 23.3 g/(m³h) over a period of 49 days with a minimum of 22.8 g/(m³h). In this test, the mean efficiency was 93.0%. Since both tests were still running, further results on long-term stability will be available soon.

4. Conclusions

It was confirmed that sufficient oxygen supply in active aerated filters enhances CH_4 oxidation. Comparing the results from the conducted aerated compost filter test with the former passive biocover tests (Felske, 2003), the long-term CH_4 degradation rate of the filter increased approximately by a factor of 5.5 from 5.1 g/(m³h) to more than 28.0 g/(m³h). In the passive system, the CH_4 oxidation occurred in a narrow horizon in the upper part of the filter, where sufficient oxygen concentrations and matching CH_4/O_2 ratios were found (Felske, 2003). The air was introduced into the headspace of the column. The depth of the CH_4 oxidation horizon was estimated to be 10–15 cm thick. With the found enhancement factor of 5.5, the whole aerated filter volume with a height of 85 cm should be activated for CH_4 oxidation. Considering the anaerobic conditions in the lower part of the filter, not all parts are involved in CH_4 oxidation. The observed EPS production in the lower part of the filter hinders CH_4 oxidation by constraining O_2 diffusion to the cells in the biofilm. In addition, the pore clogging by EPS and accumulated process water from the upper parts of the filter are leading to gas mixing problems.

To prevent pore clogging by EPS production, process water accumulation and gas mixing problems, the lower compartment of the filter should be made of material with particular high gas and water conductivity. Due to the anaerobic conditions in the lower part of the filter the total CH_4 load increased. Therefore, the CH_4 oxidation capacity of the upper part of the filter should be higher than calculated.

The found mean CH_4 degradation rate of 28.5 g/(m³h) can be used for a simplified estimation of the required filter volume for poor LFG treatment. Assuming a LFG flow of 30 m³/h and a CH_4 content of 30%, the aerated biofilter has to have a volume of about 230 m³ with a CH_4 degradation efficiency of 96%.

With higher gas flow rates, higher temperatures and the associated drying of the filter material, the moisturizing of the material is essential. The decreasing CH_4 oxidation efficiency in the compost filter test was reversible by moisturizing the filter. Because the dry compost material had hydrophobic properties, the moisturizing process took 12 days before nearly 100% CH_4 oxidation efficiency was re-established. At the moment reliable online measurement of water contents in loose compost substrates is hardly feasible. Therefore, the moisturizing of all gas input flows and precautionary irrigation of the aerated filter material is recommended.

With the variations in the total air inlet flow and the distribution to the three air input levels, the CH_4 oxidation is spread more evenly over the filter volume. The optimum utilization of the whole filter is characterized by a linear decrease in the CH_4 concentrations taking the dilution into account. On the other side, by reducing and varying the air input the CH_4 oxidation efficiency of the filter stayed below 100%. Therefore, the optimum ratio between air input flow and CH_4 load has to be worked out in further investigations.

References

- AbfAbIV, 2001. Verordnung über die umweltverträgliche Ablagerung von Siedlungsabfällen.
- Barlaz, M.A., Green, R.B., Chanton, J.P., Goldsmith, C.D., Hater, G.R., 2004. Evaluation of a biologically active cover for mitigation of landfill gas emissions. *Environ. Sci. Technol.* 38 (18), 4891–4899.
- Bogner, J., Spokas, K.A., Burton, E.A., 1997. Kinetics of methane oxidation in a landfill cover soil: temporal variations, a whole-landfill oxidation experiment, and modeling of net CH_4 emissions. *Environ. Sci. Technol.* 31 (9), 2504–2514.
- Christensen, T.H., Kjeldsen, P., Lindhardt, B., 1996. Gas-generating processes in landfills. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), *Landfilling of Waste: Biogas*. E&FN Spon, London.
- EEA, 2001. http://themes.eea.eu.int/Environmental_issues/air_quality/indicators/ozone_precursors/AP_5.pdf (accessed 04/01/05).
- EEG, 2000. Gesetz für den Vorrang Erneuerbarer Energien.
- Felske, C., 2003. Minimierung von Restgasemissionen aus Siedlungsabfalldeponien durch Methanoxidation in Deponieabdeckschichten, Forum Siedlungswasserwirtschaft und Abfallwirtschaft, 20, University Duisburg-Essen.
- Hilger, H.A., Cranford, D.F., Barlaz, M.A., 2000. Methane oxidation and microbial exopolymer production in landfill cover soil. *Soil Biol. Chem.* 32 (4), 457.
- Hilger, H.A., Liehr, S.K., Barlaz, M.A., 1999. Exopolysaccharide control of methane oxidation in landfill cover soil. *J. Environ. Eng.*, 1113–1123.
- Humer, M., Lechner, P., 1997. *Grundlagen der biologischen Methanoxidation*. Verlagspostamt 1190, Wien.
- IPCC, 2001. Climate change 2001: the scientific basis. In: Houghton, J.T., Ding, Y., Griggs, D.J., van der Linden, P.J. (Eds.), *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.
- Streese, J., Stegmann, R., 2003. Microbial oxidation of methane from old landfills in biofilters. *Waste Manage.* 23 (7), 573–580.
- TASi, 1993. Technische Anleitung zur Verwertung, Behandlung und sonstigen Entsorgung von Siedlungsabfällen.
- UBA, 2003. <http://www.env-it.de/umweltdaten/jsp/document.do?event=downloadImage&ident=4893> (accessed 3/30/05).
- Weast, R.C., 1985. *Handbook of Chemistry and Physics*, 66th ed. CRC Press Inc., Boca Raton.
- Wilshusen, J.H., Hettiaratchi, J.P.A., De Viss, A., 2004. Methane oxidation and formation of EPS in compost: effect of oxygen concentration. *Environ. Pollut.* 129 (2), 305–314.