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Landfill gas distribution at the base of passive methane oxidation biosystems: Transient state analysis of several configurations

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A B S T R A C T

The design process of passive methane oxidation biosystems needs to include design criteria that account for the effect of unsaturated hydraulic behavior on landfill gas migration, in particular, restrictions to landfill gas flow due to the capillary barrier effect, which can greatly affect methane oxidation rates. This paper reports the results of numerical simulations performed to assess the landfill gas flow behavior of several passive methane oxidation biosystems. The concepts of these biosystems were inspired by selected configurations found in the technical literature. We adopted the length of unrestricted gas migration (LUGM) as the main design criterion in this assessment. LUGM is defined as the length along the interface between the methane oxidation and gas distribution layers, where the pores of the methane oxidation layer material can be considered blocked for all practical purposes. High values of LUGM indicate that landfill gas can flow easily across this interface. Low values of LUGM indicate greater chances of having preferential upward flow and, consequently, finding hotspots on the surface. Deficient designs may result in the occurrence of hotspots. One of the designs evaluated included an alternative to a concept recently proposed where the interface between the methane oxidation and gas distribution layers was jagged (in the form of a see-saw). The idea behind this ingenious concept is to prevent blockage of air-filled pores in the upper areas of the jagged segments. The results of the simulations revealed the extent of the capability of the different scenarios to provide unrestricted and conveniently distributed upward landfill gas flow. They also stress the importance of incorporating an appropriate design criterion in the selection of the methane oxidation layer materials and the geometrical form of passive biosystems.

1. Introduction

Passive methane oxidation biosystems (PMOBs), which include certain types of biofilters, biowindows and biocovers that are not operated by active ventilation or other means of control, have been the focus of numerous studies in recent years. PMOBs may be constructed in the upper layers of a final cover system, in the absence of or in combination with active collection systems of landfill gas. They consist of two main layers: the gas distribution layer (GDL) and the methane oxidation layer (MOL). The gas distribution layer serves to maximize the spatial distribution of landfill gas, originating either from the underlying waste body or from a gas supply pipe, to the methane oxidation layer. The methane oxidation layer is located at the surface and is where methanotrophic bacteria oxidize CH_4 into CO_2 in the presence of molecular O_2. Several environmental parameters control the rate of methane oxidation in PMOBs, including the texture of the methane oxidation layer materials, temperature, NH_4^+ and NO_3^- contents, presence of vegetation, etc. (e.g. Chanton et al., 2011; He et al., 2012; Huber-Humer et al., 2008; Scheutz et al., 2009; Spokas and Bogner, 2011).

Regardless of the mechanism of gas flow, i.e. advection or diffusion, moisture is another key parameter affecting methane oxidation rates, because it controls gas flow behavior through unsaturated soils (e.g. Fredlund et al., 2012; Langfelder et al., 1968; Lu and Likos, 2004; Tang et al., 2011). The specific influence of soil moisture on the methane oxidation rate in a particular soil depends on its water retention characteristics and therefore varies with soil texture and degree of compaction. When the moisture content is low enough, gas is free to migrate by diffusion in the air phase or – if the pressure is high enough – by advection. When cracks are formed and the landfill gas is under pressure, gas flows mainly by advection. However, when the moisture content (or degree of saturation) increases and reaches a certain value, the upward flow of CH_4 and downward flow of O_2 through the methane oxidation layer would be greatly reduced (Adu-Wusu

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and Yanful, 2006; Bussière et al., 2003; Cabral et al., 2010). A point may be reached where the air phase is no longer continuous and gas molecules have to diffuse in the liquid phase, which significantly slows down the process. Indeed, the coefficient of diffusion of oxygen through a saturated or nearly saturated layer is approximately four orders of magnitude lower than in air (Cabral et al., 2000; Yanful, 1993). This may result in concentrated loadings at the base of the methane oxidation layer, which may lead to concentrated flow, therefore unacceptable surface CH_4 concentrations, i.e. hotspots (Rachor et al., 2013; Rower et al., 2011). Moisture accumulation in the methane oxidation layer is partly related to the capillary barrier effect along the interface between the gas distribution and methane oxidation layers (Ahoughalandari and Cabral, 2017; Tétreault et al., 2013). The capillary barrier effect is formed when a fine-textured soil overlies a coarser one. The contrasts in textural and hydraulic properties between the moisture retention layer (upper layer) and the capillary break layer (bottom layer) lead to moisture retention above the interface.

The usual concept employed in many passive methane oxidation biosystems is that of a sloped plane interface between the methane oxidation and gas distribution layers. Tétreault et al. (2013) performed steady-state numerical simulations based on estimated parameters of an experimental site in Germany and another in the Netherlands, both with sloped plane interfaces. Tétreault et al.'s (2013) results showed that the capillary barrier effect led to high degrees of saturation along most of the GDL-MOL interface. Consequently, landfill gas would be diverted towards the usually drier upslope area of these experimental plots, which has indeed been reported by Geck et al. (2012, 2016) and Röwer et al. (2012).

In order to overcome the problems posed by sloped plane interfaces, Cassini et al. (2017) proposed an ingenious concept where a series of jagged-shaped segments form the GDL-MOL interface. An experimental plot was constructed according to this concept at the AV Miljø landfill, Denmark. The idea behind the peculiar geometric concept was to ensure that landfill gas would migrate unrestricted at least in the upper part of each segment, where moisture would be low. Higher moisture content values – and possibly pore blockage by the presence of water – would be limited to the lower parts of each segment. Unrestricted refers herein to a pronounced reduction in gas flux due to the presence of water (moisture) in the pores. Considering the problem of landfill gas migration in passive methane oxidation biosystems, restriction to flow due to the presence of solid particles is disregarded. In a formal design procedure, the length of the unrestricted part of each segment would have to be calculated using appropriate design parameters, to maximize methane oxidation, and minimize hotspot formation.

In fact, most experimental plots – with jagged or sloped plane interfaces – have not been conceived following a formal design process. When this is the case, the potential restriction to landfill gas migration across the GDL-MOL interface should be assessed following clear design criteria, based on hydraulic parameters and other plausible concerns. Ahoughalandari (2016) suggested a single design criterion to incorporate the capillary barrier effect in the design of PMOBs. This criterion was denominated the length of unrestricted gas migration (LUGM). As illustrated in Fig. 1, this PMOB is characterized by a capillary barrier between the methane oxidation and gas distribution layers. LUGM is defined as the length along the interface between the methane oxidation and gas distribution layers where the pores of the methane oxidation layer material are filled with water to the extent where, for all practical purposes, they can be considered blocked to gas flow.

Ahoughalandari (2016) proposed a design parameter that allows obtaining the value of the design criterion, i.e. LUGM. The proposed design parameter is the volumetric air content associated with the threshold of unrestricted gas migration, $\theta_{a\text{-}occ}$, which can be obtained using – preferably – the air permeability function of the candidate methane oxidation layer material. Alternatively, the water retention curve or Standard Proctor curve of the methane oxidation layer material can be used. Several studies show that the degree of water saturation associated with the line of optima of the Standard Proctor curve corresponds to that associated with the occlusion of air-filled pores, i.e. $\theta_{a\text{-}occ}$ (Ahoughalandari, 2016; Jucá and Maciel, 2006; Langfelder et al., 1968; Marinho et al., 2001). This is attributed to the fact the pores of soils compacted on the wet side of optimum are in the form of discontinuous bubbles, whereas the air phase is continuous on the dry side of optimum (Leroueil and Hight, 2013). For materials where there is a gradual decrease in degree of water saturation in the vicinity of the air entry value and for which the air entry value is not well defined, it is possible to obtain the degree of water saturation associated with $\theta_{a\text{-}occ}$ using the degree of saturation associated with the air entry value (Ahoughalandari, 2016; Jucá and Maciel, 2006; Springer et al., 1998). In addition, according to Ahoughalandari (2016), the greater the horizontal distance between the isolines of the degree of water saturation on the Standard Proctor curve and the steeper the slope of the desaturation zone on water retention curve, the steeper the slope of ka-functions where $\theta_a > \theta_{a\text{-}occ}$ or $\theta_a >$ conservative $\theta_{a\text{-}occ}$. Details of the methodology to obtain $\theta_{a\text{-}occ}$ are provided in Ahoughalandari (2016). Ahoughalandari and Cabral (2017) evaluated the influence of several geometric and hydraulic parameters on the distribution of landfill gas at the base of the methane oxidation layer using LUGM as the design criterion: the smaller the value of LUGM, the smaller the region along the interface where gas could migrate unrestricted. The chances of having high surface CH_4 concentration, i.e. hotspots, would increase accordingly.

In the present study, transient-state numerical simulations were performed to assess the relative ease of landfill gas migration at the base of the methane oxidation layer of two PMOB configurations, all inspired from the technical literature (Cassini et al., 2017; Ndanga et al., 2015). The design parameters associated with the methane oxidation layer materials were identified, and the value of LUGM was obtained for each case. The quality of different designs was assessed solely based on LUGM, therefore in terms of the landfill gas flow at the base of the methane oxidation layer.

The main limitations of the present study are twofold: the first is related to the lack of consideration of evapotranspiration in the numerical simulations, and, indirectly, the importance of plant roots or vegetation in moisture release or retention. This limitation was circumvented by considering seepage rates (the flux of water that reached the top of the PMOB) as a percentage of the total precipitation. This percentage was assumed equal to that found by Cabral et al. (2010) for a reasonably similar cover design, constructed in the same landfill. The second limitation relates to the lack of consideration of water generation due to biotic activity. Evaluation of the moisture changes due to biotic activity is beyond the scope of this paper.

Future PMOBs should be designed following a robust process that includes consideration of unsaturated flow, such as presented herein. This is key to the adoption of PMOBs in the reduction of total greenhouse gas emissions from landfills.

2. Material and methods

2.1. Site configurations and associated materials

2.1.1. Modified Danish concepts 1 and 2

The *modified Danish concept* 1 was based on an experimental PMOB (12 m × 42 m) built in the AV Miljø landfill, Denmark (Cassini et al., 2017). The configuration of this concept included