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A two-dimensional gas flow model for layered municipal solid waste landfills

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ABSTRACT

Recovery and utilisation of landfill gas (LFG) can not only reduce the greenhouse effect but also permit the generation of electricity. A good understanding of gas migration from the waste body to the LFG extraction system is required to permit efficient gas recovery. This paper presents an analytical two-dimensional gas flow model to predict the distribution of gas pressure, the CH_4 emission flux, the distance of influence and recovery efficiency in landfills. The model is indicative of the flow towards a combined extraction system of vertical wells and horizontal gravel-filled trenches. Moreover, the model has a horizontal layered structure to accommodate anisotropy of municipal solid waste (MSW) and vertical variations in both gas generation rate and permeability. The relevant governing equations for multiple homogenous layers were combined using continuity conditions of gas pressure and flux at the layer interfaces, subjected to realistic boundary conditions, and then solved using an eigenfunction expansion approach. The solution was compared with data available in the literature, and a parametric evaluation was performed to understand the roles of the relevant variables. The results show that, for a non-homogeneous model, the maximum pressure appears at the upper layer of the landfill rather than at the bottom. The location of the maximum pressure depends on the assumptions regarding the vertical distributions of the LFG generation rate and permeability. Additionally, the results can be used to form preliminary estimates of LFG recovery efficiency and overall landfill stability for different waste compositions.

1. Introduction

Landfill gas (LFG) is generated through chemical and biological processes of the municipal solid waste (MSW) mainly under anaerobic conditions. The stable anaerobic phase generally starts 5–6 months after waste placement [1]. First-order waste decay models are widely used to estimate changes in LFG generation empirically [2–4]. The generated LFG is mainly composed of methane (45–60%) and carbon dioxide (40–55%) with trace amounts of other gases such as sulphur dioxide or volatile organic compounds [5]. Both methane and carbon dioxide are greenhouse gases and may cause health risks for on-site workers. Moreover, methane presents an explosion risk at concentrations between 5% and 15% by volume in the presence of O_2. For these reasons, it is important to incorporate features into the landfill design to collect and remove gas efficiently. Another motivation of recovery is that a gas rich in methane is a potential renewable energy resource. As a result, LFG collection systems are extensively used to control the escape of gases and achieve effective gas recovery. Thus, a good understanding of gas migration in landfill wastes is essential to provide a rational basis for the engineering design of LFG collection systems.

Both analytical and numerical solutions have been developed to predict gas transport in MSW landfills. To simplify the solving process, most of the analytical solutions assume a homogeneous gas generation rate [6–8] or permeability of MSW [6–11]. However, the gas generation rate and permeability of MSW show great non-homogeneity with respect to depth due to compression, degradation and a non-homogeneous distribution of moisture content [12,13]. Li et al. [14] provided a solution for gas flow in layered landfills and concluded that the layered characteristics of MSW should be considered in the prediction of gas pressure in landfilled wastes. And yet, this model was one dimensional, and only the vertical flow of the gas was considered. Alternatively, numerical methods can be used to study complex conditions, and some numerical solutions [15,16] have considered the non-homogeneity of MSW. Jung et al. [15] proposed a two dimensional layered model to evaluate the

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Nomenclature

m	number of individual homogeneous layers
i	integer ranges from 1 to m
H	total thickness of the landfill (L)
s_i	LFG generation rate per bulk volume of the ith layer ($M\,L^{-3}\,T^{-1}$)
K_{vi}, K_{hi}	vertical and horizontal gas permeability of the ith layer, respectively (L^2)
θ_g	gas content
t	time (T)
p_i	absolute gas pressure of the ith layer ($M\,L^{-1}\,T^{-2}$)
R_g	gas constant ($L^2\,T^{-2}\,K^{-1}$)
μ	dynamic viscosity of gas ($M\,L^{-1}\,T^{-1}$)
T	absolute temperature (K)
x	horizontal distance from centre of the slot well (L)
z	vertical distance from top of the landfill (L)
x_w	slot well position (L)
x_f	half the distance between wells (L)
A_i	combined parameter of the ith layer ($M^2\,L^{-4}\,T^{-4}$)
k_i	degree of ith layer anisotropy (K_{hi}/K_{vi})
ϕ_i	absolute gas pressure squared of the ith layer ($M^2\,L^{-2}\,T^{-4}$)
n	integer ranges from 1 to infinite
X	eigenfunction ($M\,L^{-1}\,T^{-2}$)
λ	eigenvalue (L^2)
a_{in}, b_{in}, c_{in}, d_{in}	integration parameter ($M\,L^{-1}\,T^{-2}$)
f_z	vertical gas flux ($M\,L^{-2}\,T^{-1}$)
L_0	potential LFG generation capacity ($M\,L^{-3}$)
c'	degradation rate constant (T^{-1})
ρ_{CH4}, ρ_g, ρ_{MSW}	density of CH_4, LFG and MSW, respectively ($M\,L^{-3}$)
e	void ratio
S_l	liquid saturation
Q_{ox}, Q_{em}	oxidised and emitted methane, respectively ($M\,L^{-1}\,T^{-1}$)
Q_g, Q_c	total generated and collected LFG, respectively ($M\,L^{-1}\,T^{-1}$)
σ_{ox}	soil oxidation fraction
Q_w	recovered gas at the well ($M\,L^{-1}\,T^{-1}$)
Q_{ae}	air intrusion at the top ($M\,L^{-1}\,T^{-1}$)

influence of a permeable layer on LFG collection and fugitive methane emissions. Tinet and Oxarango [16] investigated the gas migration in an axisymmetric domain around a vertical extraction well considering the effect of mechanical settlement on hydraulic properties. Although numerical solutions can consider complex geometries and inhomogeneous material properties, they are complicated and require significant time commitments for coding and computation, as in these previous studies. Moreover, the available studies involving numerical models made simplifying assumptions that considered the horizontal and vertical wells separately, even though these act together in real landfills.

In this paper, an analytical model was developed to study the gas flow towards combined LFG collection systems in layered landfills. Although the drainage system for gas in landfills typically consists of a combination of vertical wells and horizontal drains with typical spacings [17,18], as shown in Fig. 1a, this is too complex to consider in an analytical model. As a simplification, the vertical wells and horizontal drains were considered as a slot well, i.e., plane ABDC in Fig. 1b. In this case, drainage of gas may occur in the vertical direction towards a surface drain as well as horizontally towards the slot drain (lines AB and GH). Moreover, the model is two dimensional and has a horizontal layered structure to accommodate the anisotropy of the MSW and vertical variations in both gas generation and permeability. This layered structure allows the model to demonstrate the sensitivity of estimates of the gas pressure distribution and the influence distance to anisotropy and vertical non-homogeneity. The relevant governing equations for multiple homogenous layers were combined using continuity conditions of gas pressure and flux at the layer interfaces, subjected to realistic boundary conditions, and then solved using an eigenfunction expansion approach. The solution was verified against a field investigation of CH_4 emission flux in the Tianziling landfill, China. Furthermore, the distribution of gas pressure, the CH_4 emission flux, the distance of influence and recovery efficiency were calculated to investigate the influences of various physical and operating parameters of MSW landfills.

2. Mathematical model

LFG collection systems, which generally consist of vertical wells and horizontal gravel-filled trenches [17], are shown in Fig. 1. The shape of vertical wells layout is triangular in general. This practical landfill geometry cannot be described by an axisymmetric model. Three dimensional models are computationally expensive and may not provide a significant advantage over simpler two dimensional models. Note that the liquid permeability of gravel-filled trenches (>10^{-2} cm/s) is nearly two orders of magnitude larger than that of MSW (10^{-4}~10^{-3} cm/s) [17,19]. The liquid permeability can be used to derive the magnitude of the intrinsic permeability. Moreover, the higher field capacity of MSW results in much lower gas permeability [20,21]. Therefore, a rectangular cross section (plane ABHG in Fig. 1) is considered to simulate the gas flow towards slot wells (lines AB and GH). Additionally, with the focus on gas migration in MSW landfills, the coupling effects of multi fields can also be simplified in this model and mainly reflected in the layered characteristics of wastes. A schematic of this two-dimensional flow system is shown in Fig. 1c. The landfill was divided into m individual homogeneous layers, each having its own LFG generation rate per bulk volume s_i (kg m^{-3} s^{-1}), vertical gas permeability K_{vi} (m^2) and horizontal gas permeability K_{hi} (m^2). The subscript i indicates different layers from the top to the bottom. The total thickness of the landfill is H (m).

Thus, considering vertical [7,14] and horizontal transport of LFG in a homogeneous waste layer, the governing equation of mass conservation can be written as

$$\frac{\partial}{\partial t}\left(\theta_g \frac{p_i}{R_g T}\right) = \frac{\partial}{\partial x}\left(\frac{K_{hi}}{\mu}\frac{p_i}{R_g T}\frac{\partial p_i}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{K_{vi}}{\mu}\frac{p_i}{R_g T}\frac{\partial p_i}{\partial z}\right) + s_i, \qquad (1)$$

where θ_g is the gas content of the waste (volume of gas per bulk volume); t is the time (s); p_i is the absolute gas pressure of the ith layer (Pa); R_g is the gas constant (J kg^{-1} K^{-1}); μ is the dynamic viscosity of LFG (kg m^{-1} s^{-1}); T is the absolute temperature (K); x is the horizontal distance from the centre of the slot well (m), and z is the vertical distance measured from the top of the landfill (m).

The assumptions of the model were as follows: (1) LFG, which can be assumed to be an equimolar mixture of CH_4 and CO_2, behaved as an ideal gas with constant gas content and dynamic viscosity; (2) LFG transport can be described by Darcy's law neglecting gravitational effects [7,9,14]; (3) the diffusional flow was neglected because it does not have an appreciable impact on gas pressure predictions [22]; (4) the temperature was temporally and spatially uniform [7,14,23]; and (5) gas-flow within the landfill was a steady state process as the time required for the layer to