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Research Paper

A model for gas pressure in layered landfills with horizontal gas collection systems

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ABSTRACT

The recovery and emission of landfill gas (LFG) is an important topic in landfill management. To produce an effective engineering design for an LFG collection system, designers must understand the migration of gas from the waste body to horizontal extraction wells. This paper develops a two-dimensional analytical solution to enable the study of the gas pressure distribution, well pressure and recovery efficiency in layered landfills with horizontal wells. A horizontal layered structure is used to accommodate the non-homogeneity of various municipal solid waste (MSW) aspects with respect to depth, including gas generation, permeability and temperature. The governing equations, subject to boundary and continuity conditions, are solved by using separation of variables and double finite integral transforms. The solution was verified against another analytical solution and a numerical simulation. Subsequently, a sensitivity analysis of single-well model parameters is performed to optimize a double-well system. The results show that a landfill with horizontal collection systems cannot be assumed to be one dimensional with increasing well spacing. Additionally, both the operational vacuum and maximum gas pressure can be reduced through the design of a double- or multiple-well system. Therefore, the proposed solution can be used for the verification of more complex models and the preliminary design of a horizontal well system.

1. Introduction

This paper is an extension of an analytical gas flow model developed by Feng and Zheng [1], who used a horizontal layered structure to accommodate the anisotropy and vertical non-homogeneity of municipal solid waste (MSW). The previous study considered the vertical wells and horizontal drains as a slot well, which was only used to properly describe the gas flow toward a combined extraction system. However, certain landfill operators must collect the landfill gas (LFG) before the landfill reaches the final grade. Under such circumstances, the use of a horizontal gas collection system can be an effective solution [2]. Thus, it is necessary to understand the gas migration from the waste body to horizontal extraction wells to enable the effective engineering design of LFG collection systems. And the previous solution is not applicable for such scenario. Generally, landfills with horizontal wells were simplified to be one dimensional (especially for analytical models [2,3]), but the assumption may also not be reasonable under certain conditions. There have been some two-dimensional numerical models [4,5] to describe the leachate recirculation using horizontal wells. Few studies have focused on the scenario of horizontal gas collection systems, and even less by analytical methods.

In this paper, a two-dimensional analytical solution is derived to study the gas flow in layered landfills with horizontal extraction wells. The non-homogeneity of various MSW aspects with respect to depth in gas generation, permeability and temperature can be accommodated by the horizontal layered structure. Arbitrary number of horizontal pipes are installed in each layer with different pumping rates. The governing equations, subject to boundary and continuity conditions, were solved using separation of variables and double finite integral transforms. The solution was verified against another analytical solution and a numerical simulation. Subsequently, the gas pressure distribution, well pressure and recovery efficiency were calculated to investigate the influence of horizontal well spacings and depths, well pumping rates and non-homogeneity of the MSW. Furthermore, a double-well system was optimized based on a sensitivity analysis of the single-well model parameters. The proposed solution can be used for the verification of more complex models and the preliminary design of a horizontal well system.

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Nomenclature

The following symbols are used in this paper:

M	number of individual homogeneous layers
i	integer ranging from 1 to M
H	total thickness of the landfill (L)
L	model width (L)
s_i	LFG generation rate per bulk volume of the ith layer ($ML^{-3}T^{-1}$)
T_i	absolute temperature of the ith layer (K)
h_i	thickness of the ith layer (L)
K_{vi}, K_{hi}	vertical and horizontal gas permeability of the ith layer, respectively (L^2)
N	number of horizontal pipes in each layer
j	serial number of horizontal pipes from 1 to N
x	horizontal ordinate (L)
z	vertical distance from the top of the landfill (L)
(x_{ij}, z_{ij})	coordinates of the jth horizontal pipe in the ith layer (L)
q_{ij}	pumping rate of the jth horizontal pipe in the ith layer ($ML^{-1}T^{-1}$)
θ_g	gas content
t	time (T)
p_i	absolute gas pressure of the ith layer ($ML^{-1}T^{-2}$)
R_g	gas constant ($L^2T^{-2}K^{-1}$)
μ	dynamic viscosity of gas ($ML^{-1}T^{-1}$)
k_i	degree of ith layer anisotropy (K_{hi}/K_{vi})
z_{i-1}, z_i	top and bottom vertical coordinates of the ith layer, respectively (L)
$P_{i-1}(x)$, $P_i(x)$	gas pressure at $z = z_{i-1}$ and z_i, respectively ($ML^{-1}T^{-2}$)
p_{atm}	atmospheric pressure ($ML^{-1}T^{-2}$)
u_i	new function ($M^2L^{-2}T^{-4}$)
m	integer ranging from 0 to infinity
n	integer ranging from 1 to infinity
λ_m	separation constants (L^{-2})
a_{im}, b_{im}	integration parameters ($ML^{-1}T^{-2}$)
α_m, β_{in}	$\alpha_m = m\pi/L$ and $\beta_{in} = n\pi/h_i$ (L^{-1})
f_{zi}	vertical gas flux for the ith layer ($ML^{-2}T^{-1}$)
L_0	potential LFG generation capacity (ML^{-3})
c'	degradation rate constant (T^{-1})
e	void ratio
S_l	liquid saturation
abs(Δp)	gas pressure difference between the two- and one-dimensional models ($ML^{-1}T^{-2}$)

2. Mathematical model

When focusing on gas migration in MSW landfills, the multi-field coupling effect can be simply reflected in the horizontal layered structure [1,3]. A schematic of this two-dimensional flow system is shown in Fig. 1. The landfill was divided into M individual homogeneous layers, each having its own LFG generation rate per bulk volume s_i ($kg\,m^{-3}\,s^{-1}$), temperature T_i (K), vertical gas permeability K_{vi} (m^2) and horizontal gas permeability K_{hi} (m^2). For each layer, N horizontal pipes are installed at the coordinates (x_{ij}, z_{ij}) with pumping rates q_{ij} ($kg\,m^{-1}\,s^{-1}$). The subscript i indicates the different layers from top to bottom, and j is the serial number of the horizontal pipes ($j = 1, 2, \ldots, N$). The total thickness of the landfill is H (m), and the model width is L (m). If $N = 1$ and $x_{i1} = L/2$, L can be called the horizontal well spacing.

In this study, the LFG was assumed to behave as an ideal gas with constant gas content and dynamic viscosity, and LFG transport can be described by Darcy's law neglecting gravitational effects [3,6–8]. The diffusional flow was neglected because it does not have an appreciable impact on gas pressure predictions [9]. The delta function (δ) was used here to model the effects of pumping from horizontal pipes [6]. Thus, considering vertical [2,3] and horizontal [1,6] transport of LFG in a homogeneous waste layer, the governing equation of mass conservation can be written as

$$\frac{\partial}{\partial t}\left(\frac{\theta_g p_i}{R_g T_i}\right) = \frac{\partial}{\partial x}\left(\frac{K_{hi} p_i}{\mu R_g T_i}\frac{\partial p_i}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{K_{vi} p_i}{\mu R_g T_i}\frac{\partial p_i}{\partial z}\right) + \left[s_i - \sum_{j=1}^{N} q_{ij}\delta(x - x_{ij})\delta(z - z_{ij})\right], \quad (1)$$

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 (277 $J\,kg^{-1}\,K^{-1}$); μ is the dynamic viscosity of the LFG (1.37×10^{-5} $kg\,m^{-1}\,s^{-1}$); x is the horizontal ordinate (m); and z is the vertical distance measured from the top of the landfill (m).

Additionally, the gas-flow within the landfill was assumed to be a steady-state process because the time required for the layer to respond to changes in the gas generation rate should be considerably less than that required for significant changes in the gas generation rate to be realized [2]. Thus, Eq. (1) can be rewritten as

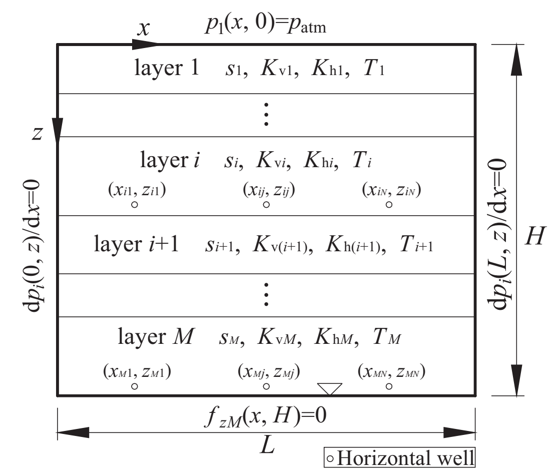

Fig. 1. The schematic of the two-dimensional gas flow system.

$$k_i\frac{d}{dx}\left(p_i\frac{dp_i}{dx}\right) + \frac{d}{dz}\left(p_i\frac{dp_i}{dz}\right) + \frac{\mu R_g T_i}{K_{vi}}\left[s_i - \sum_{j=1}^{N} q_{ij}\delta(x - x_{ij})\delta(z - z_{ij})\right] = 0, \quad (2)$$

where

$$k_i = \frac{K_{hi}}{K_{vi}}. \quad (3)$$

The boundary conditions for each layer are as follows:

$$\frac{dp_i}{dx}(0, z) = 0, \quad \frac{dp_i}{dx}(L, z) = 0, \quad \text{at } z_{i-1} \leqslant z \leqslant z_i, \quad (4a)$$

$$p_i(x, z_{i-1}) = P_{i-1}(x), \; p_i(x, z_i) = P_i(x), \quad \text{at } 0 \leqslant x \leqslant L, \quad (4b)$$