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A gas flow model for layered landfills with vertical extraction wells

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ABSTRACT

This paper developed a two-dimensional axisymmetric analytical model for layered landfills with vertical wells. The model uses a horizontal layered structure to describe the waste non-homogeneity with depth in gas generation, permeability and temperature. The governing equations in the cylindrical coordinate system were transformed to dimensionless forms and solved using a method of eigenfunction expansion. After verification, the effects of different well boundary conditions and gas extraction systems on recovery efficiency were investigated. A dimensionless double-layer system, consisting of a cover and a waste layer, was also explored. The results show that a constant vacuum pressure boundary condition can be enough to describe a perforated pipe surrounded by drainage gravel with a reasonable value of well radius, such as half the radius of gravel fill. Also, the 7 independent variables (one marked with an asterisk is dimensionless) of a double-layer system can be integrated into 3 dimensionless ones: Cover permeability K_{v1}^*/(Vertical gas permeability of waste $K_{v2}^* \times$ Cover thickness h_1^*), − Vacuum pressure $p_w \times P_{atm}K_{v2}^*/(\mu R_g T_2 \times$ Gas generation rate of waste s_2) and ln(Well radius r_w^*)/(Anisotropy degree of waste k_2^*). The integration is based on the inherent mechanism of this flow system with certain simplification. The effects of these variables are then quantitatively characterized for a better understanding of gas recovery efficiency. Same recovery efficiency can be achieved with different variable combinations. For example, increasing h_1^* (such as doubling it) has the same effect with decreasing K_{v1}^* (such as halving it). Along with the reduction of variables by half, the integration can facilitate the preliminary design, and is a small but important advance in the consideration of MSW non-homogeneity.

1. Introduction

This paper is an extension of analytical landfill gas (LFG) flow models for combined extraction systems and horizontal extraction systems developed by Feng and Zheng (2015), Feng et al. (2015). In these models, a horizontal layered structure was used to describe the anisotropy and vertical non-homogeneity of municipal solid waste (MSW). However, vertical wells are most common and effective after the landfill closure even though other configurations have been used (Townsend et al., 2015). Thus, it is necessary to investigate the gas migration in layered landfills with vertical wells to create a tool for effective engineering design.

The recovery efficiency of LFG relates to many factors, such as MSW property (gas generation, permeability and anisotropy), initial design (cover, well radius and spacing), operational and management conditions (vacuum pressure) (Cai et al., 2014; Jain et al., 2005; Powell et al., 2016). Some other factors like methane oxidation and storage (Spokas et al., 2006) will not be studied in this paper. As for vacuum pressure, a constant value is generally specified throughout the vertical well to describe its extraction effect (Yu et al., 2009). This boundary condition differs from the realistic vertical well modelled by Tinet and Oxarango (2010). The reasonability and applicability of constant vacuum pressure assumption needs to be discussed. Moreover, the non-homogeneity of MSW cannot be neglected since a homogeneous assumption of gas generation and permeability will result in an incorrect prediction of gas flow and recovery in landfills (Feng and Zheng, 2015; Tinet and Oxarango, 2010). However, how to represent the MSW non-homogeneity in the design process without using numerical solutions is a big problem to many engineers who use standards and criterions. The analytical solutions for a layered structure model are simpler than the numerical solutions, but their application remains difficult mainly because of too many variables. To the authors' knowledge, few studies have ever addressed this problem.

In this paper, a two-dimensional (2D) axisymmetric analytical model was developed for layered landfills with vertical wells. A

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Nomenclature

The following symbols are used in this paper (dimensionless form in parentheses)

m number of individual homogeneous layers
i integer ranging from 1 to m
H total thickness of the landfill [L]
R model radius or vertical well spacing [L]
s_i LFG generation rate per bulk volume of ith layer $[\mathrm{M\,L^{-3}\,T^{-1}}]$
T_i absolute temperature of ith layer [K]
h_i (h_i^*) thickness of ith layer [L]
K_{vi} (K_{vi}^*), K_{hi} (K_{hi}^*) vertical and horizontal gas permeabilities of ith layer $[\mathrm{L^2}]$
z (z^*), r (r^*) vertical and radial coordinates [L]
θ_g volumetric gas content
t time [T]
P_i absolute gas pressure of ith layer $[\mathrm{M\,L^{-1}\,T^{-2}}]$
R_g LFG constant $[\mathrm{L^2\,T^{-2}\,K^{-1}}]$
μ LFG dynamic viscosity $[\mathrm{M\,L^{-1}\,T^{-1}}]$
k_i (k_i^*) degree of ith layer anisotropy (K_{hi}/K_{vi})
r_w (r_w^*) vertical well radius [L]
P_w, p_w absolute and relative pressures at the well $[\mathrm{M\,L^{-1}\,T^{-2}}]$
P_{atm} atmospheric pressure $[\mathrm{M\,L^{-1}\,T^{-2}}]$
z_{i-1}, z_i (z_{i-1}^*, z_i^*) top and bottom vertical coordinates of ith layer [L]
A_i combined parameter of ith layer $[\mathrm{M^2\,L^{-2}\,T^{-4}}]$
u_i new function $[\mathrm{M^2\,L^{-2}\,T^{-4}}]$
X, λ eigenfunction and eigenvalue
n integer ranges from 1 to infinite
c_{in}, d_{in} integration parameters $[\mathrm{M\,L^{-1}\,T^{-2}}]$
g_n integral of Bessel functions of the first kind (J_0, J_1) and second kind (Y_0, Y_1)
f_{zi}, f_{ri} vertical and radial gas flux for ith layer $[\mathrm{M\,L^{-3}\,T^{-1}}]$
L_0 potential LFG generation capacity $[\mathrm{M\,L^{-3}}]$
c' degradation rate constant $[\mathrm{T^{-1}}]$
e, S_l void ratio and liquid saturation
Q_p flow rate of LFG into the vertical pipe $[\mathrm{M\,L^{-1}}]$
r_p, r_d radii of perforated pipe and drainage gravel fill [L]
f_{sk} a coefficient that considers the skin effect
V_{pipe} velocity averaged over a pipe section $[\mathrm{L\,T^{-1}}]$
C_{HL} head loss coefficient valid for laminar flow conditions $[\mathrm{M\,L^{-3}\,T^{-1}}]$
A_c ratio of collection area to the waste volume $[\mathrm{L^{-1}}]$
x_w, x_f slot well position and spacing [L]
R_i radius of influence [L]
A_{min}, B, a_1, a_2, a_3, a_4 fitting parameters
b_1, b_2, …, b_7, b_8 fitting parameters

horizontal layered structure was also used to describe the non-homogeneity of MSW with depth in gas generation, permeability and temperature. The governing equations were transformed to dimensionless forms and solved using a method of eigenfunction expansion. Other analytical and numerical models were used for verification. Subsequently, the gas pressure and recovery efficiency were calculated to study the effects of different well boundary conditions and LFG collection systems. A dimensionless double-layer system (a cover and a waste layer), which is the simplest problem encountered in landfills, was then quantitatively analysed. The independent variables of this system were integrated for the preliminary design and future research. The work is a small but important advance in the consideration of MSW non-homogeneity for design.

2. Mathematical model

The multi-field coupling effect can be simply modelled using a horizontal layered structure when focusing on the gas migration in landfills (Feng and Zheng, 2015; Li et al., 2012). The gas migration around a vertical well is a 2D axisymmetric problem, and its schematic is shown in Fig. 1. The landfill, with a total thickness of H (m) and a model radius (half distance between two neighbouring wells) of R (m), was divided into m individual homogeneous layers. Each layer has its own LFG generation rate per bulk volume s_i ($\mathrm{kg\,m^{-3}\,s^{-1}}$), vertical and horizontal gas permeability [K_{vi}, K_{hi}] ($\mathrm{m^2}$), and temperature T_i (K). The subscript i means the serial number of layers from top to bottom.

The governing equations of LFG flow in layered landfills with vertical wells are established based on the same assumptions with Feng and Zheng (2015), Feng et al. (2015). Briefly speaking, the LFG was an ideal gas (Li et al., 2012) with its flow following the Darcy's law (Arigala et al., 1995; Wise and Townsend, 2011; Young, 1989) and neglecting the effect of diffusion (Massmann, 1989). More details can be found in previous models. Thus, considering vertical (Li et al., 2012; Townsend et al., 2005) and horizontal (Feng and Zheng, 2015; Young, 1989) migration of LFG in the cylindrical coordinate system, the governing equation for each homogeneous layer can be written as

$$\frac{\partial}{\partial t}\left(\frac{\theta_g P_i}{R_g T_i}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{K_{hi}P_i}{\mu R_g T_i}\frac{\partial P_i}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{K_{vi}P_i}{\mu R_g T_i}\frac{\partial P_i}{\partial z}\right)+s_i, \tag{1}$$

where θ_g is the volumetric gas content; t is the time (s); P_i is the absolute gas pressure of the ith layer (Pa); R_g is the LFG constant ($277\,\mathrm{J\,kg^{-1}\,K^{-1}}$); μ is the LFG dynamic viscosity (1.37×10^{-5} $\mathrm{kg\,m^{-1}\,s^{-1}}$); r is the radial coordinate (m); and z is the vertical coordinate representing the depth (m).

As the required time for responding to changes in gas generation rate s_i should be considerably less than that for remarkable

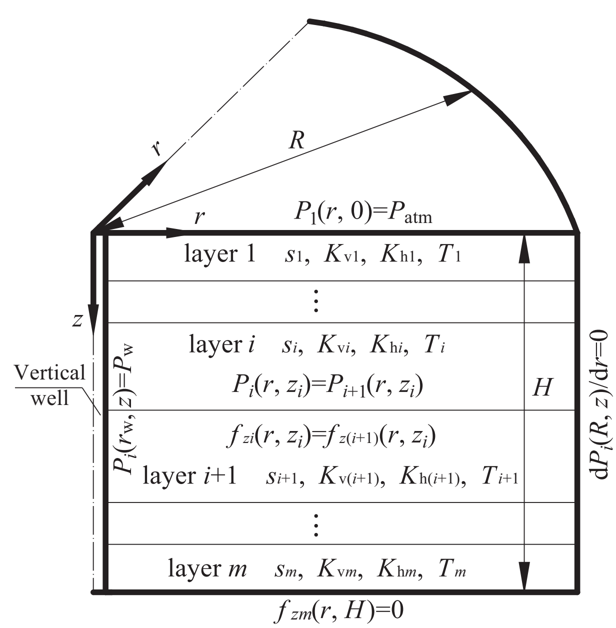

Fig. 1. The schematic of gas flow system with a vertical well.