THE FRAMEWORK OF A NUMERICAL MODEL FOR GAS EXTRACTION FROM MUNICIPAL SOLID WASTE LANDFILLS

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ABSTRACT
A preliminary model, under development, to determine concentration profile in a landfill is presented. The presented model will be part of a numerical model for analysis of gas flow during gas extraction process. Concentration profile determined by the preliminary model will represent initial conditions for the gas extraction model. The model considers heterogeneity in landfills such as spatial variation in gas generation and presence of intermediate covers. Laboratory setup is being developed to generate data for model calibration and verification.

RÉSUMÉ
Ce papier présente une model préliminaire, encore a l'étude, destine a déterminer un profil de concentrations dans un sol donne. Ce modèle sera ensuite inclus dans un modèle numérique afin d'analyser le flux du gaz durant son extraction. Le profil des concentrations, calculée par le modèle préliminaire, servira de condition initiale au modèle extraction du gaz. Ce modèle interprète les heterogeneites de la roche comme des variations spatiales dans la création du gaz et comme un signe de la présence de couche intermediare. Des mesures sont réalisées en laboratoire afin de calibrer et de vérifier le modèle.

1. INTRODUCTION

Landfill gas consist typically 40-60% methane and rest carbon dioxide water vapour and other trace gases. Estimates of annual global methane emissions from landfills vary between 30 and 70 million tons (Bingemer and Crutzen 1987). After certain treatment landfill gas (LFG) can be utilized for energy generation purposes. It is reported that landfills operated by the City of Vancouver contain 200 million GJ of energy, enough to meet Vancouver's electrical power demands for more than six years (Sperling and Henderson 2001). Extraction of landfill gas for energy recovery has other advantages as well, such as decreased risk of landfill fires/explosion hazard and decreased emission of greenhouse gases. Considering the economic potential and environmental issues associated with landfill gas many landfill managers are opting to extract landfill gas for energy generation.

A number of models have been developed in past for gas flow in landfills. A one dimensional radial flow model was developed by Lu & Kunz, (1981) which uses LFG pressure and pressure changes caused by the withdrawal of gas to calculate the landfill's methane production rate and gas flow permeability. A single well model was proposed by Esmaili (1975). The model does not consider the gas generation in landfill. Findikakis and Leckie (1979) developed a one dimensional model for flow of a mixture of methane, carbon dioxide and nitrogen through sanitary landfills. Young (1989) developed an analytical model for flow inside a non-isotropic porous medium with an arbitrary number of horizontal extraction pipes. Solution was used to predict the consequences of cumulative failure within a complex pumping system, and hence estimate the circumstances under which gas is first able to escape from a site. Arigala et al. (1995) presented a three dimensional model, which is an extension of Young's model. Model allows for both horizontal and vertical orientation of wells. El-Fadel et al (1996) developed a numerical model to predict generation and transport of gas and heat in sanitary landfills. Perera (2001) developed a one-dimensional advective-dispersive-reactive gas migration model. This model estimates the source strength of methane immediately below the final cover, not within the waste itself (Perera 2001).

A landfill is a heterogeneous environment and some heterogeneity like spatial variation in gas generation rates, and presence of intermediate covers play a significant role in gas dynamics. This paper presents a preliminary model to determine concentration profile in landfill prior to gas extraction from landfill, which will be part of a gas extraction model. Model considers the spatial variation in gas generation rates and the effect of intermediate covers on gas flow, Model will be calibrated and verified with laboratory data for which a setup is being developed.

2. MODEL DEVELOPMENT

Once anaerobic conditions have been established, gas generated in a landfill consist mainly methane and carbon dioxide. Due to air ingress in shallow regions in landfill oxygen may be present in significant amounts. Gas generated in landfill moves laterally to surrounding soil, and vertically to escape through the covers into the atmosphere (Perera et al. 2002). Most of the gas generation models including "Scholl Canyon model" and "LANDGEM" are based on first order reaction kinetics. Thus for a particular waste mass reaction rate decreases with time due to decrease in substrate concentration. Since a landfill is filled over a period of time gas generation rate are different for different waste masses in landfill resulting in spatial variation in gas generation rates. Presence of intermediate covers in landfill also affects dynamics of gas in landfills. Esmaili (1975) reported a considerable difference in gas composition in test cells where intermediate covers were present from the cells where those were absent.

2.1 Theoretical Formulation

Transport of each species in the gas mixture can be described by advection-dispersion-reaction equation given in Equation 1 (Poulsen et al. 2001, El-Fadel et al. 1996, Findikakis and Leckie 1979).

$$\varphi \frac{\partial C_i}{\partial t} = -\frac{\partial (v_k C_i)}{\partial x_k} + \frac{\partial}{\partial x_k}\left(D_i^s \frac{\partial C_i}{\partial x_j} \right) + G_i \qquad [1]$$

Where: φ is air porosity of waste (m^3 of voids/ m^3 of waste), C_i is concentration of the i^{th} component (Kg/m^3), v_k is Darcy's velocity in k^{th} direction (m/day), t is time (days), x_k is distance in k^{th} direction (m), D_i^s is diffusion coefficient of species i in porous medium (m^2/day) and G_i is the generation rate for species i (Kg/m^3/day).

The Darcy velocity v_k can be determined from Darcy's equation (Equation 2).

$$v_k = -\frac{k_a}{\mu_m}\frac{\partial P}{\partial x_k} \qquad [2]$$

Where: k_a is air permeability of waste (m^2), μ_m is dynamic viscosity of gas mixture (Pa-day) and P is pressure (Pa).

Assuming the gas mixture obeys ideal gas law, the pressure exerted by a mixture of m gases is given by Equation 3.

$$P = \sum_{i=1}^{m} \frac{R}{M_i} C_i T \qquad [3]$$

Where: R is universal gas constant (8.314 Joule/mole/^{o}K), M_i is molecular weight of species i (Kg/mole), T is absolute temperature (^{o}K).

The viscosity of a mixture of m gases can be determined by Wilke method using Equations 4a and 4b (Reid et al. 1987).

$$\mu_m = \sum_{i=1}^{m} \frac{y_i \mu_i}{\sum_{j=1}^{m} y_j \theta_{ij}} \qquad [4a]$$

$$\theta_{ij} = \frac{\left\{ 1 + \left(\frac{\mu_i}{\mu_j} \right)^{1/2} \left(\frac{M_j}{M_i} \right)^{1/4} \right\}^2}{\sqrt{8}\left(1 + \frac{M_i}{M_j} \right)^{1/2}} \qquad [4b]$$

Where: μ_i is viscosity of gas i (Pa-day), y_i and y_j are mole fractions of gas i and j respectively, M_i and M_j are molecular weights of gas i and j respectively.

Air diffusion coefficient (D_i^a)of gas i in a mixture of m gases is given by Equation 5 (Reid et al. 1987).

$$D_i^a = \frac{1 - y_i}{\sum_{\substack{j=1 \\ j \neq i}}^{m} \frac{y_j}{D_{ij}}} \qquad [5]$$

Where: D_{ij} is the diffusion coefficient of gas i in a binary mixture of gases i and j. Diffusion coefficient of gas i in porous medium can be determined using relation given in Equation 6 (Troeh et al. 1982).

$$\frac{D_i^s}{D_i^a} = \left[\frac{\varphi - c}{1 - c} \right]^d \qquad [6]$$

Where: c and d are constants that depend on the porous medium characteristics. For a soil in which air porosity ranges between 0.1-0.5, c = 0.05 and d = 1.4 (Troeh et al. 1982).

The rate of gas generation based on first order reaction kinetics is given by Equation 7.

$$G_i = -A_i k L_0 e^{-kt} \qquad [7]$$

Where: k is gas generation rate constant (day^{-1}), L_0 is ultimate gas generation potential of waste (Kg/m^3), A_i is the fraction of species i in gas generated and t represents the age of waste mass. Above equation is valid for methane and carbon dioxide among the LFG components being considered in the model because no O_2 is generated from waste.

Since it takes many years to fill landfill age of waste masses increase and generation rates decrease with depth in a landfill. Assuming the waste was filled at constant rate the age of waste (t) in equation 7 can be expressed as (Arigala et al. 1995):

$$t = t_0 + t_f \left(\frac{Z}{D} \right) \qquad [8]$$

Where: t_0 is time since closure of landfill, t_f is total time to fill the landfill, Z is the depth of waste mass measured from surface and D is the total depth of landfill.

A rectangular cross section of landfill is shown in figure 1. Landfill is divided into layers based on the location of intermediate covers. Intermediate covers act as a low permeability barrier to gas flow. Origin for Cartesian coordinates is at upper left corner. X direction is taken from left to right and Y direction is downwards.

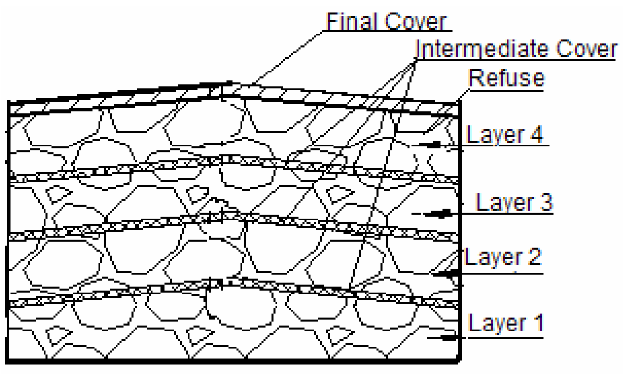

Figure 1. Schematic of Cross Section of a Landfill

2.2 Initial Condition and Boundary Conditions

Initial time for model is considered the time when landfill was closed. As initial condition, the concentrations at different sections are determined assuming the gas generated after application of the intermediate cover is retained there. Age of intermediate cover and age waste at a section can be determined from Equation 8. If the age of waste at a section at the time of closure of landfill is t_w and time since application of intermediate cover is t_{IC}, then the concentration of specie i in a layer at initial time is given by:

$$C_{i,t=0} = A_i L_0 \left[e^{-k(t_w - t_{IC})} - e^{-kt_w} \right] \qquad [9]$$

Since only CH_4 and CO_2 are being generated from waste, above equation is valid for these two components. It is assumed that anaerobic conditions have been established in each layer and all O_2 has been depleted by the time of landfill closure except for final cover where concentrations is equal to the concentration in atmosphere. Concentrations at the interface of waste and cover are same as the concentrations in waste at the interface and it varies linearly in intermediate covers.

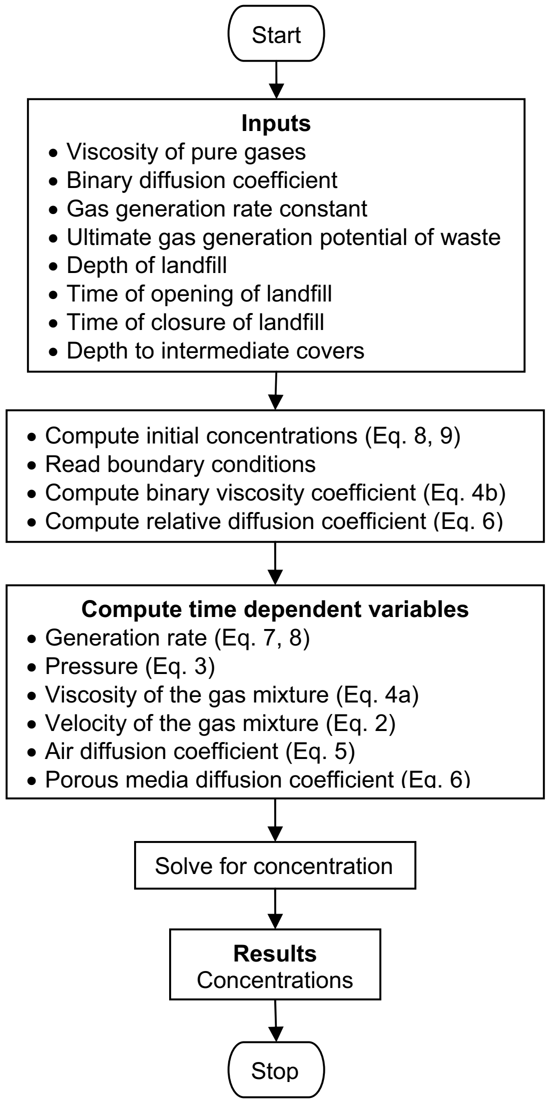

Figure 2. Flow Chart of model

The lower boundary is assumed impermeable to gas transport thus the flux in vertical direction is zero at bottom boundary. Concentrations in a thin layer at the top are assumed same as atmospheric concentrations. Only advective flow is assumed across side boundaries. The boundary conditions can be written as:

$$\frac{\partial C_i}{\partial y} = 0, \qquad y = D \qquad [10]$$

$$C_i = C_{i,atm}, \quad y = 0 \qquad [11]$$

By continuity at side boundaries:

$$\left.\frac{k_a}{\mu_m}\frac{\partial P}{\partial x}\right|_{refuse} = \left.\frac{k_a}{\mu_m}\frac{\partial P}{\partial x}\right|_{soil} \qquad x = 0, x = L \qquad [12]$$

Where: L is landfill width. Parameters on left correspond to refuse and those on right side correspond to soil outside landfill boundary.

2.3 Solution Technique

A computer program in MATLAB 6.0 will be developed to run model. Figure 2 shows a flow chart for model. A finite difference technique will be used to solve model. A laboratory setup is being developed to generate data for model calibration and verification.

3. CONCLUSION

A preliminary numerical model to determine concentration profile in landfill is presented, which will be part of a numerical model for gas extraction from landfills. Model considers the effect of intermediate covers and spatial variation in gas generation due to variation in age of waste in different layers. Results from preliminary model will represent initial condition for gas extraction model.

Model needs to be calibrated for which a laboratory setup is being developed. Model will be improved further to incorporate effect of permeability variation with depth.

4. ACKNOWLEDGEMENTS

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