SIMULATION OF LANDFILL GAS PRODUCTION RATE AND METHANE CONCENTRATION: MODELLING AND VERIFICATION THROUGH FIELD MEASUREMENTS

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Abstract - Landfill Gas (LFG) is mainly consists on methane () and carbon dioxide (CO_2). CH_4 concentrations is important for the estimation of the potential for electric energy production form LFG. Most of the models used to estimate the LFG production rate and CH_4 the content of LFG do not take into account the reduction of concentration with time, as a result of air diffusion into the landfill, especially during the last phase of methanogenesis and during maturation phase of landfilling. The present study proposes modifications to the EPA's Landgem model for the simulation of the aforementioned parameters. Onsite measurements in Fodele landfill, Heraklion, Greece indicated that the model simulation results are close the measured values. Thus the modified Landgem model may be used to estimate the potential for electric energy production from landfills.

Keywords - landfill, biogas, Waste to Energy, Landgem, LFG, methane

I. INTRODUCTION

Landfill Gas (LFG) production in a landfill site is related to Municipal Solid Waste (MSW) quality, deposition rate, climate conditions in area of the landfill site and the presence of toxic substances such as heavy metals, H_2S (Vavilin, 2006; Rasi et al., 2011). LFG production reaches to its maximum value at about 12 months after landfill's close (USA EPA, 2016). EPA's Landgem (Landfill Gas Emissions Model) (USA EPA, 2016) is the most widely known model for simulation of LFG production on landfill sites, among a large number of models that have been proposed (Aydi et al, 2015; Broun and Sattler, 2016; Cho et al., 2012; Emkes et al., 2015). Landgem, uses first-order kinetics to simulate LFG production rate, assuming that LFG contains 50% v/v of CH_4 (USA EPA, 2016).

However, methane concentration in LFG is pretty stable for a long time, approximately 15-20 years (USA EPA, 2016) during the phase methanogenesis (Figure1), and depends on the organic matter in MSW that have been disposed in the landfill. However, it has been observed that after a period of time, CH_4 concentration is gradually drops with time, during the last phase of methanogenesis and during the maturation phase (Fig. 1) (Bove, 2006; Ozkaya, 2007), not only due to the substrate depletion (Bove, 2006) but also due to air intrusion into the landfill (Bozkurt et al., 1999; Pawlowska, 2014). The present study aims to modify EPA's Landgem model (newest version, v3.02 released in 2005) taking into account the main mechanisms of air introduction in a landfill cell (as have been proposed by Bozkurt et al., 1999), so to estimate both the LFG production rate and the CH_4 concentration in LFG, for long periods of time, and ti verify its findings with field studies.

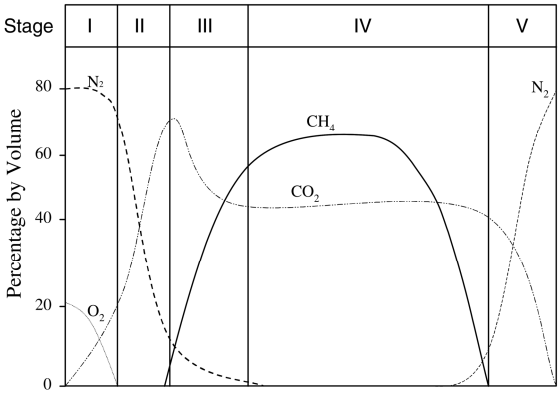


Figure 1. LFG gases during the various stages (adopted from Bove et al. (2006)). Phase I: Aerobic decomposition, Phase II: Initial phase of acetogenesis, Phase III: Final phase of acetogenesis, Phase IV: Methanogenesis, Phase V: Maturation phase.

II. APPLICATION SITE

Experiments carried out at the landfill of Heraklion, Crete, Greece, which is located near Fodele village, at the site of Pera Galinoi. The landfill receives MSW from the greater Heraklion area, serving a population of about 238,000 inhabitants. The landfill comprises of four distinct parts: two older dump sites "A" and "B" and two newer landfill cells "A" and "B". A new cell (cell "C") is currently in operation. The Dump site "B" has a volume of about 0.53 Mm^3, it was receiving MSW from 1992 to 1998 and is currently sealed. Dump site "A" has a volume of about 1 Mm^3 and was in operation between 1998 to 2008. Cell "A'' has a volume of about 0.72Mm^3 as was in operation between 2009-2012. Finally, Cell "B" has a volume of about 0.79 Mm^3 and is currently ready to be sealed. According to Manasaki et al. (2016), the typical composition of MSW, at Fodele Landfill is: food residues (39%), paper (20 %), plastics (17.5%), leather-wood-fabric-tires (4.7%), glass (4.25%),

metals (6%), inert materials (3%) and non-classified wastes (5.55%). LFG is currently collected only from dump sites "A" and "B" and cell "A", and conveyed to a central collector via the LFG collection system for flaring out in a flare tower. LFG from cell "B" is to be transferred for flaring also, when this cell will be sealed. The operator of the Fodele landfill is currently considering to exploit the energy content of the produced LFG, for electric energy production. Thus a realistic estimation of LFG production and methane content is important.

III. MODELING

3.1 Governing equations

As the landfill site in Fodele consists of various cells, which have closed during different times, both, the quantity and quality of LFG produced by each site, should be estimated indecently. The CH_4 production, as predicted by Landgem motel is given by Equation 1.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{h=0.1}^{1} kL_0 \left(\frac{M_i}{10} \right) e^{-kt_{i,j}} \quad (1)$$

Where
Q_{CH4}: Total annual production of CH_4 (m^3/yr),
L_0: CH_4 production potential (m^3CH_4/tn MSW)
k: CH_4 production rate (yr^{-1})
n: The year of calculation from the cell closure
i: Annual time step
j: Annual time step equal to 10% of the year
M_i: The annual quantity of MSW entering in the landfill at year i
$t_{i,j}$: Age of the j^{th} part of the M_i MSW in year i

Atmospheric air is intruded into the landfill body from around the membrane seal, as a result of excess LFG pumping (which results to negative pressure inside the landfill body) or simply due to diffusion the atmospheric air through poorly sealed areas, resulting to the dilution of the LFG components (CH_4 and CO_2). The general partial differential equation (PDE) governing the concentrations of air components (N_2 and O_2), in every cell is derived from the mass balances according to Equation 2 (Bozkurt et al., 1999).

$$\varepsilon_p \frac{\partial \left(c_i V_j \right)}{\partial t} + q_j \frac{\partial \left(c_i V_j \right)}{\partial x} = D_{2,i} \frac{\partial^2 \left(c_i V_j \right)}{\partial x^2} + R_i V_j \quad (2)$$

Where
q_j: LFG pumping rate at cell or dump site (m^3/hr)
ε_p: The porosity of MSW in a cell
c_i: The concentration of air component i (mol/m^3)
V_j: Volume of a cell or dump site (m^3)
$D_{2,i}$: the diffusion coefficient of air (m^2/h)
R_i: The reaction rate of atmospheric component i (mg/m^3hr)
x: The main direction of air movement

Hence, the following system of PDEs is formed

$$\begin{cases} \varepsilon_p \dfrac{\partial \left(c_{O_2} V_j \right)}{\partial t} + q_j \dfrac{\partial \left(c_{O_2} V_j \right)}{\partial x} = D_{2,O_2} \dfrac{\partial^2 \left(c_{O_2} V_j \right)}{\partial x^2} + R_{O_2} V_j \\ \varepsilon_p \dfrac{\partial \left(c_{N_2} V_j \right)}{\partial t} + q_j \dfrac{\partial \left(c_{N_2} V_j \right)}{\partial x} = D_{2,N_2} \dfrac{\partial^2 \left(c_{N_2} V_j \right)}{\partial x^2} \\ \varepsilon_p \dfrac{\partial \left(c_{CO_2} V_j \right)}{\partial t} + q_j \dfrac{\partial \left(c_{CO_2} V_j \right)}{\partial x} = D_{2,CO_2} \dfrac{\partial^2 \left(c_{CO_2} V_j \right)}{\partial x^2} + R_{CO_2} V_j \end{cases} \quad (3)$$

N_2 is an inert gas, thus it does not involved in reactions. Atmospheric O_2 can react with organic matter to produce CO_2; the reaction rate, considering first order kinetics, is expressed by Equations 4 and 5:

$$R_{O_2} = -k_{O_2} c_{O_2} \quad (4)$$

$$R_{CO_2} = k_{O_2} c_{O_2} \quad (5)$$

As it is shown in Figure 2, a protective cover layer of a geo-membrane, of thickness L_1, has been placed between the atmosphere and MSW in accordance with the requirements of environmental legislation. The diffusion coefficient for the protective layer is denoted as D_1 (m^2/h). Cell's average depth is denoted as L_2 (m).

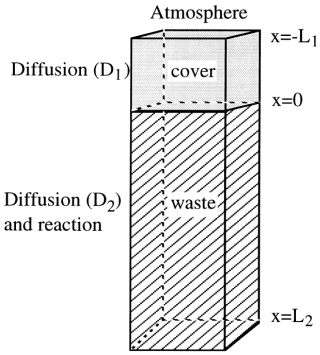


Figure 2. Schematic representation of air components intrusion in a landfill cell or a dump site, though the sealing membrane (Bozkurt et al., 1999)

The boundary conditions of the above system are given by Equations 6 and 7:

$$D_{2,i} \frac{dc_i}{dx}|_{x=0} = \frac{D_1}{L_1} \left(c_i \left(x = 0 \right) - c_i \left(x = L_1 \right) \right) \quad (6)$$

$$\frac{dc_i}{dx}|_{x=L_2} = 0 \quad (7)$$

While the initial conditions are given by Equation (8)

$c_{O2}(t=0)=c_{N2}(t=0)=0$ and $c_{CO2}(t=0)=C_{CO2,0}$ (8)

The decrease of CH_4 concentration of with time in the various cells and dump sites of Fodele landfill, based on the above equations, is presented in Figure 3.

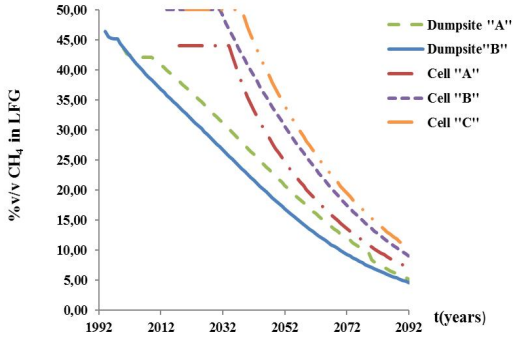


Figure 3. Simulation of CH_4 fraction in LFG with time, at each site of Fodele landfill.

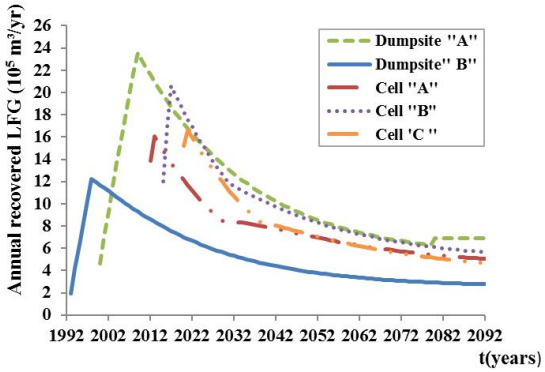


Figure 4. Simulation of the annual LFG production rate in the various sites of Fodele landfill, baed on the modified Landgem model.

3.2 Paramaters selection

Each landfill is unique, thus the various parameters may vary from site to site. The parameters employed in the present study for LFG production and LFG dilution, have been derived from the literature (Amini et al., 2012; Bozkurt et al., 1999; Cho et al., 2016; Fei et al., 2016). The CH_4 production potential has been assumed as L_0=96m^3CH_4/tn MSW for both dump sites and for cell "A", while for cell "B", where L_0 was assumed as 77m^3CH_4/tn MSW. The CH_4 generation rate, was taken as k= 0, 01yr^{-1}.

In case of LFG dilution modeling the MSW porosity is considered to be ε=0.35, while the geomembrane diffusion coefficient has been assumed as D_1=0.631 m^2/h and waste diffusion coefficient as $D_{2,i}$= 20600 m^2/h. The oxygen reaction rate has been assumed as $k_{O2}=5\cdot10^{-7}$ h^{-1}. Pumping rates at each dumpsite have been assumed equal to the LFG production (Equation 1). The volumes from each cell or dumpsite estimations are presented in the Table 1. The LFG recovery efficiency was estimated to 50% and 75% for dumpsites dump sites "A" and "B" and cells "A" and "B", respectively. The annual LFG production rates of Heraklion Landfill, estimated with the modified Landgem model, are shown in Figure 4.

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IV. FIELD MEASUREMENTS

A series of field measurements had been taken place, (August-September, 2016), for the measurement of LFG quantitative and qualitative characteristics, in each cell or dump site. The field results were compared with the simulated outcome. LFG analyses were conducted by a portable Geotech Biogas5000, UK, LFG analyzer which can measure both the LFG major gases concentration (CH_4, CO_2, O_2 and H_2S) and LFG flowrate (via Pittot tube). The measurements were taken place in the main LFG streams and at the collective pipeline, upstream of the flare. The measured values and model predictions of CH_4 concentration and the LFG production rate for Dumpsite "A" and Cell "A" and for the joint stream of Dumpsite "A" and Cell "A" are shown in Table 1. Measurements did not conduct in Cell "B" and Cell "C", as the first was not sealed, yet, while the second was still active. Also, measurements did not conduct in Dumpsite "B" as it was depleted and was decided that the LFG from this site will not be utilized for electric energy production.

LFG	Field measured values			Modified Landgem model predictions		
	Dumpsite "A"	Cell "A"	Joint stream	Dumpsite "A"	Cell "A"	Joint stream
% v/v CH_4	39.2±1.8	44.6±1.9	41.8±1.13	42.05	50	45.50
Q_{LFG} (m^3/h)	219.4±18	198.6±9.25	354.8±53.5	211.27	162.37	373.64

Table 1. Quantitative and qualitative characteristics of Fodele landfill LFG, measured and simulated values.

The deviation between predicted values for CH_4 concentration and for the LFG production rate and the respective measured values for Dumpsite "A" and Cell "A" and for the joint stream are shown in Figure 5.

The deviations of the simulated values from the measured ones, for CH_4 concentration were 7.27%, 12.10% and 6.46%, for Dumpsite "A", Cell "A" and for their combined stream, respectively, while, for LFG production rate were 3.70%, 18.24% and 5.31%, respectively. The model predictions in both cases were close enough to the measured values, taking into account the complexity of landfilling processes.

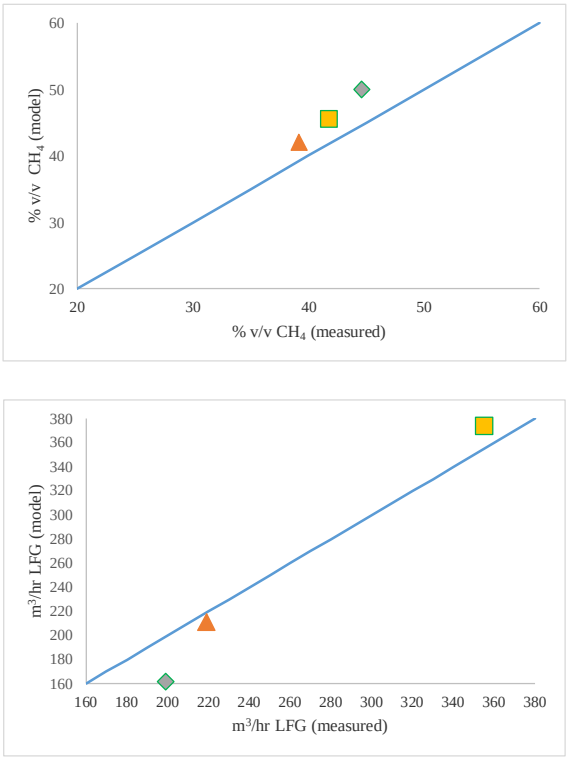


Figure 5. Deviation between the model's prediction and measured values for LFG production rate (Above) and for CH_4 concentration (Below). Triangle: Dumpsite ''A'', Rhomb: Cell ''A'', Square: Joint stream of Cell ''A'' and Dumpsite "A".

CONCLUSIONS

The LFG production from Fodele landfill, in Heraklion, Greece, has been estimated based on the modified Landgem model, which takes into account the reduction of CH_4 concentration in LFG, with time, due to atmospheric air intrusion into the landfill body. Model predictions have been compared with field measurements and have been found to lie close by. Thus, simulation results may be taken into account for estimating the long term potential for electric energy production from the landfill.

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