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Applying Simple Numerical Model to Predict Methane Emission from Landfill

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Abstract: The aim of this study is utilizing weighted residual method, a kind of numerical models, which leads to a simpler model for users. Utilizing the simplified numerical models helps landfill owners and decision makers for an easier understanding of methane emission. In this study, three different numerical models with five bench marks have been developed to estimate methane gas generation of a considered landfill: (i) linear polynomial function for boundaries and trail function, (ii) linear function for trail and second order polynomial function for boundaries satisfaction and (iii) second order polynomial function for boundaries satisfaction and Sin shape function for trail function. Second one as the best fitted one with SD of 0.76 has been selected.

Key words: Landfill gas, methane emission, numerical model, Nauerna landfill

INTRODUCTION

Methane gas is a valuable energy resource and the leading anthropogenic contributor to global warming after carbon dioxide. Atmospheric methane concentrations have doubled over the last 200 years and continue to rise, although the rate of increase is slowing (Sadamasa *et al.*, 2007). By mass, methane has 21 times the global warming potential of carbon dioxide over a 100 year time frame (EPA, 1999).

Municipal solid waste landfills contribute a high portion of greenhouse gases generation in the world. Due to the organic nature of most wastes, it is the microbial processes that govern the gas generation process (Christopherson, 2001).

As it has been mentioned, landfill gas (LFG) mainly includes Carbon Dioxide and Methane. On this basis estimation of LFG generation rates is conducted (1) to satisfy regulatory requirements associated with estimating Non-Methane Organic Carbon (NMOC) emissions; (2) to assess the impact of landfill-generated methane on global warming, (3) as part of the design of LFG and methane control systems; and (4) to provide information necessary to evaluate and design LFG-to-energy projects (Manna *et al.*, 1999).

Since methane has more negative impact on global air warming and also is important to take into account for LFG-to-energy, most of emission estimation models estimates CH_4. Several previous studies have developed models to describe methane production from landfills according to Darcy's Law, physical characteristics such as climate, refuse mass and age, the Gompertz Equation and environmental factors such as moisture content, sulfate and volatile solids (Ozakaya *et al.*, 2006). Almost all of the current worldwide used models are first order decay ones. In these models, generated methane has a direct relation with carbon content of the waste and exponential function of decay rate by time as follow (Gardner and Robert, 1999):

$$\text{Methane production} \propto Lo^{*}e^{-kt} \tag{1}$$

TNO model obeys the above mentioned rule. In fact, TNO model calculates LFG generation based on degradation of organic carbon in the waste (Scharff and Jacob, 2006). USEPA has developed a software with the name of LandGEM which uses almost the same formula for municipal solid waste. LandGEM uses the first-order decomposition rate equation (Eq. 2) to estimate annual emissions over a specified time period (EPA, 2005).

$$Q_{CH_4} = \sum_{i=1}^{n} kLoMi(e^{-kt}) \tag{2}$$

Where:

Q_{CH4} = Annual methane generation in the year of the calculation (m^3 $year^{-1}$)

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n = (year of the calculation) - (initial year of waste acceptance)
k = Methane generation rate ($year^{-1}$)
Lo = Potential methane generation capacity (m^3 Mg^{-1})
Mi = Mass of waste accepted in the ith year (Mg)
ti = Age of waste mass in the ith year ($year^{-1}$)

Since there are different fractions of organic carbon in different materials (i.e., the fraction degradable of paper, garden waste and food waste are different from each other) (IPCC, 1996), it looks like that the models should be revised. On this basis, multiphase models have been provided to consider the composition of wastes. Gassim, software provided by UK environmental agency, works by multiphase model concept (Environmental agency, 2003). Afvalzorg is another multiphase model on predicting LFG production which takes advantage of considering eight waste categories and three fractions. Each fraction is contemplated separately for purposes of LFG production estimation. The multi-phase model is a first-order model and can be described mathematically by Eq. 3 as follow (Scharff and Jacob, 2006):

$$\alpha_t = \varsigma \sum_{i=1}^{3} 1.87 A C_{0,i} k_{1,i} e^{-k_{1,i} t} \quad (3)$$

Where:
α_t = Landfill gas formation at a certain time (m^3 $year^{-1}$)
ς = Dissimilation factor
i = Waste fraction with degradation rate $k_{1,I}$ (kg $i.kg_{waste}^{-1}$)
A = Amount of waste in place (tonne)
C_0 = Amount of organic carbon in waste (kg tonne $waste^{-1}$)
$k_{1,i}$ = Degradation rate constant of fraction i ($year^{-1}$)
t = Time elapsed since depositing (y)

EPER France is another multiphase model which consider three different degradation rate for waste composition (Scharff and Jacob, 2006).

There is a zero order model, EPER Germany, can be described mathematically by Eq. 4 as follow (Scharff and Jacob, 2006):

$$Me = M^* \, BDC^* \, BDC_f \, ^*F \, ^*D \, ^*C \quad (4)$$

Where:
Me = Amount of diffuse methane emission (Mg $year^{-1}$)
M = Annual amount of land filled waste (Mg)
BDC = Proportion of biodegradable carbon (MgC Mg $waste^{-1}$)
BDC_f = Proportion of biodegradable C converted into LFG (%)
F = Calculation factor of carbon converted into CH4
D = Collection efficiency (active degassing 0.4; no recovery 0.9; active LFG recovery and cover 0.1)
C = Methane concentration (%)

As it has been mentioned, all the above models are based on first order decay models. It seems that there is a need for estimating LFG generation in a simpler method like numerical models. On these bases, this study has been carried out to develop a simple numerical approach to predict methane emission.

MATERIALS AND METHODS

All above mentioned models has been applied for Nauerna landfill (Scharff and Jacob, 2006). The Nauerna landfill, in the Netherlands, has a total surface of 72 ha, of which 68 ha has been used to dispose of waste from 1985 and the site is still in operation. From that time to 2004 a total of 9.4 $*10^6$ Mg of waste was landfilled at Nauerna. The annual amounts of different types of waste are presented in Fig. 1. As it is clear from the figure, waste at the Nauerna landfill is not only characterized by a low content in organic matter, it also contains organic matter that is not readily biodegradable. It is notable that LFG extraction was started in 1997 and its extent increased in 2000.

Methane emission was measured in 2001 and 2002 with three techniques as follow (Scharff and Jacob, 2006):

- Mobile Plume Measurement with Tuneable Diode Laser (TDL);
- Stationary Plume Measurement (SPM) and
- Mass Balance Measurement (MBM)

Utilizing all above mentioned models and comparison of results with the measurements for Nauerna Landfill, shows that Afvalzorg multiphase model is the best fitted one (Scharff and Jacob, 2006). Table 1 shows dumped waste and results of Afvalzorg model in a glance.

Weighted residual method (WRM) is a numerical method to approximate analytically (Afshar, 2002). In fact WRM generates finite volume method, finite element method and spectral methods. On this basis, WRM has been chosen to approximate the best fitted curve for the methane generation in Nauerna Landfill as described before. In this study, landfill methane generation is estimated by two variables: (i) time (t) and (ii) dumped waste (w). Therefore, utilizing WRM method, the approximation of the generated methane can be written mathematically by Eq. 5 as follow:

Table 1: Landfilled waste and estimation of methane production in different years

year	1985	1986	1987	1988	1989	1990	1991
t	0	1	2	3	4	5	6
Waste (ton)	263.24	392.8	479.18	596.4	425.71	438.05	470.95
Methane estimation (ton)	0	0.07	0.22	0.32	0.53	0.7	1.04
Year	1992	1993	1994	1995	1996	1997	1998
t	7	8	9	10	11	12	13
Waste (ton)	542.93	688.95	604.63	579.95	343.44	232.39	417.48
Methane estimation (ton)	1.38	1.63	1.92	2.14	2.23	1.94	1.7
Year	1999	2000	2001	2002	2003	2004	
t	14	15	16	17	18	19	
Waste (ton)	565.55	579.95	688.95	481.23	415.42	195.37	
Methane estimation (ton)	1.75	1.65	1.67	1.58	1.5	1.46	

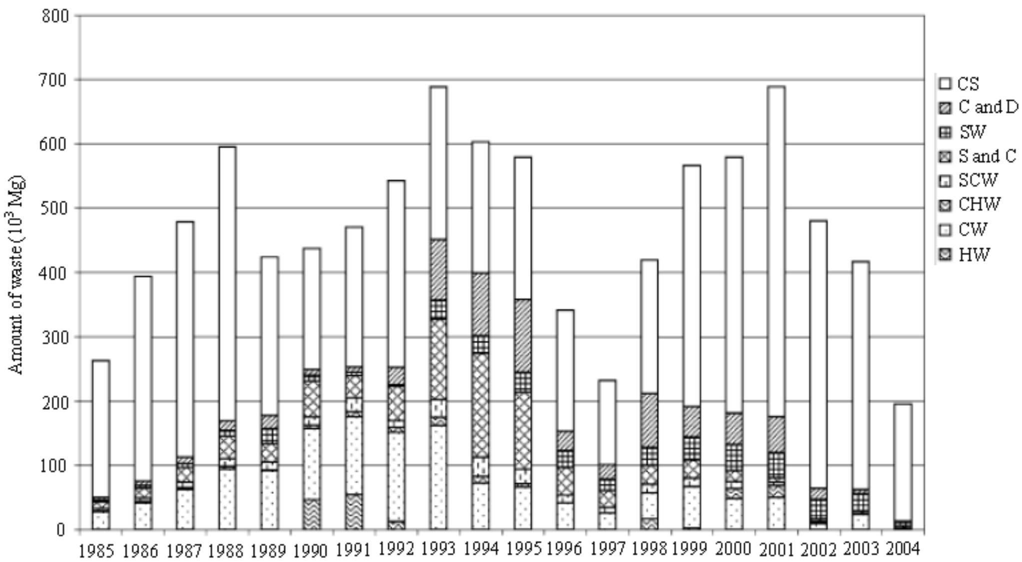

Fig. 1: Characteristics of waste in Nauerna Landfill in different years (Scharff and Jacob, 2006)

$$G \cong \psi - \sum_{n,m=1}^{K} (a_{mn} N_{mn}) \quad (5)$$

ψ is chosen to satisfy boundary condition. N is trail function which should be zero on boundaries and a is coefficient which should be determined. The goal of WRM is to choose a_{mn} such that residue (R) becomes small over a chosen domain. In fact, R is difference between right and left side of Eq. 5. Weighting function (w) would multiple by R to determine the coefficient a the better. On this basis, integration of weighting function by residue in the domain stands at zero (Eq. 6).

$$\iint_{domain} w_{lp} R\, dt\, dw = 0 \Rightarrow \iint_{domain} w_{lp}(G - (\psi - \sum_{n,m=1} (a_{mn} N_{mn})) = 0 \quad (6)$$

Since all functions in Eq. 6 are known, Eq. 7 will be obtained.

$$\iint_{domain} w_{lp}(G - \psi)dt\,dw = \iint_{domain} a_{mn}(w_{lp} \sum_{n,m=1} N_{mn}) \Leftrightarrow f_l = k_l \sum a_{mn} \quad (7)$$

Eq. 8 is a matrix translation of Eq. 7.

$$[k_{mn}][a_m] = [f_n] \quad (8)$$

To determine numerical estimation of methane production from Nauerna Landfill, 5 bench marks have been considered in this study, as Table 1.

In this study, w_{lp} and trail function (N) are assumed to be as Eq. 9 and 10 in all determinations.

$$w_{lp} = 1 \text{ if } t_l < t < t_{l+1},\ w_p < w < w_{p+1},\ 0 \text{ if not} \quad (9)$$

$$N_{mn} = t^m (t-19) w^n (w-263.24)(w-195.37) \quad (10)$$

As it is obligatory, N should be chosen such that is zero on boundaries. Three different ψ have been considered to be able to select the best fitted one.

RESULTS AND DISCUSSION

Case 1: A linear function for ψ has been considered as Eq. 11 such that satisfy boundary condition which are years 1985 and 2004.

$$\psi = 0.1537t+0.02151w-5.6627 \quad (11)$$

Regarding 5 bench marks, domain is divided to 4 sub domains, so there are four unknown coefficients and the matrix will be a four dimension one. Determining weighing function as Eq. 9, parameters in Eq. 8 will be obtained as Eq. 12.

$$k1p=\iint N_{lp}dtdw \quad \text{if } 1=p, \quad 0 \quad \text{if not}$$

$$f_1 = \int_{w=w1}^{w=w1+1} \int_{t=t1}^{t=t1+1} (G-\psi)dtdw \quad (12)$$

Utilizing Eq. 12 series and Eq. 8, coefficients a_{11}, a_{22}, a_{33} and a_{44} is obtained $-8.98401*10^{-12}$, $-1.1627*10^{-12}$,$-7.51106*10^{-12}$ and $-5.87273*10^{-12}$, respectively. On this basis, G function, approximation of methane generation, will be a non-linear polynomial as Eq. 13.

$$G \approx \psi-(a_{11}N_{11}+a_{22}N_{22}+a_{33}N_{33}+a_{44}N_{44}) = 0.1537t+0.02151w-5.6627+ 0.1537t+ 8.98401*10^{-12} t(t-19)w(w-263.24)(w-195.37)+ 1.1627*10^{-12} t^2 (t-19) w^2(w-263.24)(w-195.37)+ 7.51106*10^{-12} t^3(t-19)w^3(w-263.24)(w-195.37)+ 5.87273*10^{-12}t^4(t-19)w^4(w-263.24)(w-195.37) \quad 13)$$

As it is clear, methane generation can be gotten by using time and waste disposed weight in Eq. 13. Fig. 2 shows the result for analysis the sensitivity of the numerical model, the in a glance.

Case 2: With review of the procedure, it is clear that the role of ψ is much more important than.

$$\sum_{n,m=1} (a_{mn}N_{mn})$$

Therefore another attempt has been considered to improve the numerical model. In this case, by considering a second order polynomial ψ as Eq. 14 such that satisfy boundary condition which are years 1985 and 2004.

$$\psi = 10^{-7}t^2+6.8*10^{-7}w^2+0.00004tw-0.049 \quad (14)$$

Since N_{mn}, w_{pl} remain as values in case 1, k_{mn} will remain as it was and just fl is changed. Utilizing the same process of case 1. results in Fig. 3.

As it is clear from Fig. 3, numerical model with nonlinear function for the boundary satisfaction fits better with standard deviation of 0.76.

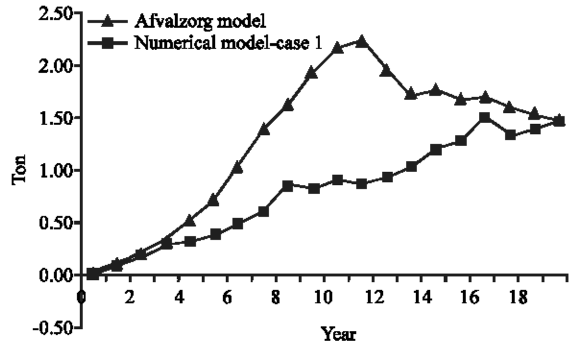

Fig. 2: Comparison of numerical model 1 with Afvalzorg model

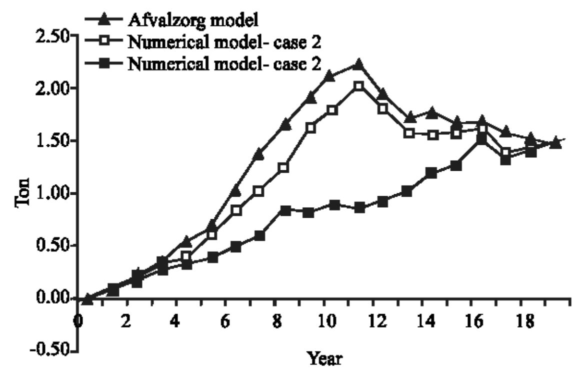

Fig. 3: Comparison of numerical model 2 with Afvalzorg model

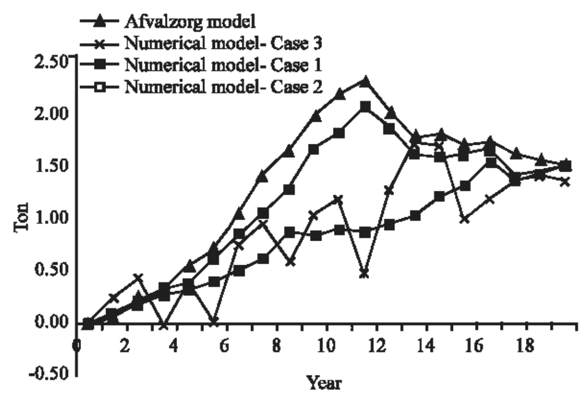

Fig. 4: Comparison of numerical model 3 with Afvalzorg model

Case 3: Sine a second order polynomial function has a good role for ψ, it was assumed that a sin shape function for trail function would be work better. On this bases, trail function is assumed as Eq. 15 and the rest parameters are remained as they are in pervious case.

$$N_{mn}=\text{Sin } mpt \text{ Sin } npw \, (w-195.37) \quad (15)$$

As it has been mentioned before, trail function should be zero on boundaries, which the above trail function is. Again, utilizing the same process of pervious cases would result in Fig. 4.

As it is clear from Fig. 4, the current numerical model is not a proper one to predict methane generation from Nauerna Landfill.

CONCLUSIONS AND RECOMMENDATIONS

As it has been described before, prediction of greenhouse gases are highly considered in international protocols. On this basis, the aim of this study is to develop a simpler approach to predict methane emission from landfills, as one of the most important portion of greenhouse gasses and also can be used as a reliable energy source.

Utilizing existing models on Nauerna Landfill shows that Afvalzorg multiphase model is the best fitted first order decay model. In this research, WRM has been established to get the objective. Three different numerical models with five bench marks have been developed and evaluated with results of the best fitted model has been ever run. The trend of fist case, which has a linear polynomial trail function and boundary satisfactory function, is the same as Afvalzorg's. It shows that this approach seems good but needs some modifications. With consideration of some changes in case 1, by having a second order polynomial boundary satisfactory function, case 2 is gained which fits better with SD of 0.76. Case 3 which has a sinus shape trail function doesn't have a reasonable result. On this basis, the numerical model in case 2 is selected the best. It is obvious that if there were more bench marks, the numerical model would be gained the better predictions.

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