A MULTIPHASE MODEL OF BIOREACTOR LANDFILL WITH HEAT AND GAS GENERATION AND TRANSFER

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Abstract. Models for gas and heat generation in landfills are generally functions of water content of each biodegradable component of the waste. Water content of each component is then assumed to be constant in time. On the other hand, bioreactor landfills are usually based on leachate recirculation where water content of waste components changes. In this work we have modified earlier models of heat and biogas generation to consider the saturation dependence of degradation kinetics of different components in a landfill and to study the temperature changes in a landfill during leachate recirculation. This paper presents first the anaerobic mathematical model of heat and gas generation and discusses the selection of particular parameters and empirical generation functions. It then presents the results of numerical simulations of a landfill during leachate injection which are compared with field measurements. The obtained results show that using this model of heat generation makes us able to model the temperature behavior of a landfill during leachate recirculation and to discuss the results of the site.

Keywords. Multiphase model, Bioreactor landfill, Heat generation, Biogas production, leachate recirculation

1. Introduction

The need to control gas and leachate production and minimize refuse volume in municipal solid waste landfills has motivated the development of landfill simulation models to predict and design optimal treatment processes. We have developed a multiphase flow model of a bioreactor landfill, using a finite volume method (Benard et al. 2003; Eymard et al. 2000), which considers the heat and gas generation and transfer.

The models for gas and heat generation in landfills are generally based on earlier works of Monod (1949), developed later by Findikakis et al. (1979), Straub and Linch (1982) and Halvadakis (1983). These models are generally functions of water content of each biodegradable component of the waste which is assumed to be constant in time. On the other hand, bioreactor landfills are usually based on leachate recirculation. Under this condition, water content of waste components changes. So it is necessary to introduce a function of saturation in gas and heat production terms, which therefore change during leachate recirculation.

In this work we have used the classical biodegradation rate model of Monod (1949) to develop a mathematical model of biogas production. Heat generation is obtained directly from the biogas production formulation. Some important hypotheses of this model are as followed:

1. The model is homogeneous and anisotropic. The anisotropy is considered as a ratio between horizontal and vertical permeability to model the stratified behaviour of a landfill because of the daily covers and compaction.
2. We consider the landfill as a three-phase porous medium. The three phases are solid waste, gas and leachate, where gas is considered as a mixture of CO2 and CH4 with equal percentages.
3. The solid phase of the landfill is considered to be non-deformable with no consolidation; it means that we just consider the effects of degradation in gas and heat production and not in deformation and settlement of the landfill.
4. The gas and liquid phases are considered to be immiscible.
5. Darcy's law is applicable for both fluid phases.
6. Thermal radiation is neglected.
7. There is a thermal equilibrium for the three phases.

Here we develop briefly the mathematical model of biogas production, introducing the parameters which are chosen and used for the bioreactor model. Numerical results are then presented and compared with the field results of temperature during leachate recirculation.

2. Biodegradation model

As solid waste is composed of different types of materials characterized by different substrate utilization rates, the total generation rate is estimated as the sum of the rates of gas generation from the individual refuse components. The
rate at which microorganism growth, death and substrate use occur can be represented by Monod’s classical model. In this model the water content of each component is considered to be constant and so it does not consider the changes of saturation during leachate recirculation. We modified this model using a function of saturation, \( f(S) \) in degradation kinetics. The saturation function is an empirical function, defined by the experimental results of bacterial activities in different saturations for biogas production. So the rate of degradation can be written as followed:

\[
\frac{dA}{dt} = A_i \lambda_i(T,S),
\]

where

\[
\lambda_i(T,S) = \lambda_i(T).f(S),
\]

\( A_i \) is the fraction of each component (i=1: rapidly biodegradable, i=2: fairly biodegradable and i=3: slowly biodegradable) and \( \lambda_i(T) \) is the degradation kinetics for each component \( A_i \) which is defined by Arrhenius Law:

\[
\lambda_i(T) = \beta_i \exp(-\frac{E_i}{RT})
\]

Here \( \beta_i \text{ (sec}^{-1}\text{)} \) is a constant and \( E_i \) is the activating energy of each component. The value of degradation kinetics depends on the characteristics of the landfill material, temperature variation but principally on the water content and saturation changes of the landfill during the degradation of organic materials. Biogas production is defined by the exponential law, proposed by Halvadakis (1983). This law works very well for anaerobic phase of degradation (Findikakis et al. 1987):

\[
\alpha_b = C_{bi} \frac{dA}{dt},
\]

where \( C_{bi} \) is the potential biogas production and \( \alpha_b \) is the rate of biogas production. Finally the rate of biogas production is obtained as followed:

\[
\alpha_b = \sum_{i=1}^{3} C_{bi} \frac{A_i(t+dt)-A_i(t)}{dt},
\]

where \( A_i(t+dt)\) and \( A_i(t) \) are respectively biodegradable masses at time \( t+dt \) and \( t \). As we can see in this model, biogas production rate depends on temperature, time and saturation. When the saturation is less than the minimum saturation which is necessary for bacterial reactions, the biodegradation stops and remains constant and there will be no biogas generation. The heat production rate is obtained directly from the biogas production rate, using the energy released for each mole of methane which is produced during degradation (H):

\[
\alpha_q = H \frac{1}{2M_b} \alpha_b
\]

where \( M_b \) is the molar mass of biogas which is considered, as mentioned, as a mixture of carbon dioxide and methane.

### 2.1. Parameters

The parameters used in the model of biogas and heat generation are presented in Tab. (1). These parameters are chosen from bibliographical researches.

<table>
<thead>
<tr>
<th>Table 1. Heat and gas production parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>( C_{bi} \text{ [m}^3\text{/kg waste]} )</td>
</tr>
<tr>
<td>( \beta_1 \text{[1/sec]} )</td>
</tr>
<tr>
<td>( \beta_2 \text{[1/sec]} )</td>
</tr>
<tr>
<td>( \beta_3 \text{[1/sec]} )</td>
</tr>
<tr>
<td>( E_i/R \text{[K]} )</td>
</tr>
<tr>
<td>( H \text{[KJ]} )</td>
</tr>
</tbody>
</table>
The values of biogas potential and activating energy are proposed by Findikakis et al. (1979) and El Fadel et al. (1996). For degradation constants we chose the average values which are proposed by Findikakis et al. (1979) and El Fadel et al. (1996) and INSA (National Institute of Applied Science, Lyon). Between the different values proposed for energy released per mole of methane we chose an average value of 50 KJ. Lanini (1998) proposed values between 40 and 255 KJ, Aran (2000) proposed values between 2 and 60 KJ and Augenstein et al. (1999) proposed an average value of 68 KJ.

Another important parameter is the saturation function which is introduced to degradation kinetics, \( \lambda(T, S) \). Definition of the saturation function is based on existing empirical knowledge: Below a minimum saturation which is essential for bacterial activities, degradation and biogas production are detained. Biogas production increases to reach its maximum value near the saturation at field capacity until the saturation equal to 1 (Gil Diaz et al., 1995). The saturation function which is used in our model is presented in Fig. (1).

![Saturation Function](image)

Figure 1. Saturation function

The hydraulic parameters are presented in Tab. (2). We used different values for porosity and hydraulic conductivity to study the effects of these parameters on temperature and to see which value matches the best numerical and in-situ curves.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.1, 0.2, 0.3</td>
</tr>
<tr>
<td>Hydrolic conductivity [m/sec]</td>
<td>1.0E-4, 5.0E-4, 1.0E-3</td>
</tr>
<tr>
<td>Initial saturation</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The choice of values of porosity and hydraulic conductivity is based on the values proposed by different researchers and we have chosen the values which are nearer to low density waste in the higher layers (Korfiatis et al., 1984; Bleiker et al., 1993; Beaven et al., 1995 and Hudson et al., 2001).

3. Model application to a real bioreactor landfill

Our model was applied to a real bioreactor landfill in France using the parameters in Tab. (1) and Tab. (2). All the other parameters for leachate recirculation like discharge flow rate, duration and temperature of leachate were obtained from the site.

This bioreactor landfill is equipped with horizontal networks for leachate recirculation and biogas collection. A leachate recirculation network design method has been developed by the Cemagref, in order to have a regular leachate distribution through horizontal drains. The waste mass is also equipped with temperature sensors to study the temperature changes of the site with time and with leachate recirculation. These temperature sensors are installed at 0, 1, 2 and 3m depth from the bottom of the top clay layer and make it possible to compare the temperature changes of the site with numerical results (see Fig. (2)).

The monitored cell is approximately 90m x 80m and 12m in depth, with five leachate recirculation lines. The last injection operation was conducted in November 2006 on a single recirculation line.
The injection parameters are presented in Tab. (3).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>First recirculation</th>
<th>Second recirculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of injection</td>
<td>7 November</td>
<td>14 November</td>
</tr>
<tr>
<td>Injection time</td>
<td>11h30-15h30</td>
<td>9h10-11h20</td>
</tr>
<tr>
<td>Discharge [m³/hr]</td>
<td>6.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Outdoor Temperature [°C]</td>
<td>2.6</td>
<td>10.7</td>
</tr>
</tbody>
</table>

4. Results and discussion

4.1. Site temperature results

Temperature data are available for a few days before injection, during and after injection, at different depths. Two of the sensors, at 0 and -3m, proved to be completely out of order. The sensor at -2m, whereas still recording reasonable temperature changes, exhibited an obvious shift of about 47°C. This shift was deduced from temperatures recorded by the -1m sensor before recirculation, assuming that before recirculation temperatures at -1m and -2m were both equal to 33°C, as shown by the -1m sensor. Using the equation below, we obtained a modified curve for T2:

\[ T_2'(t) = T_2(t) - 47°C. \]  

where \( T_2'(t) \) and \( T_2(t) \) are respectively modified and measured temperature for T2 at each time step.

4.2. Numerical results

We have used a homogeneous two-dimensional 90m x 12m model to study temperature changes during leachate injection at different depths from the injection point.

Boundary conditions are: zero-flux condition on top horizontal boundary except an injection point at the same location as on site; zero-flux condition on vertical boundaries and atmospheric pressure (perfect drainage) on bottom horizontal boundary. Discharge flow and injection duration are the same as the values in Tab. (2). As injected leachate temperature was not recorded on site, the values of 10°C and 3°C were used for the first and second injection, respectively, according to the outdoor temperature. Initial conditions are: atmospheric pressure and 25% saturation. As we have a heat and biogas production term in our model, the temperature increases slightly during two weeks before the first injection process. To reproduce a temperature of 33°C at the day of injection, we set an initial temperature of 32°C in our model.

The numerical results show the temperature changes during two injection operations. We can see the model temperature increasing during two weeks before injection in Fig. (3) and Fig. (4).
Figure 3. Temperature changes for different hydraulic conductivities and a porosity of 20%

Figure 4. Temperature changes for different porosities and a hydraulic conductivity of 1.0E-4 [m/sec]

Results are for different porosity and hydraulic conductivities of the waste. Comparing the results for T1 with site data, we can see that we have the same trends of both temperature decrease with leachate injection but after injection, site temperature increases much more rapidly than simulation temperature. We have observed that even by changing the saturation function and increasing the degradation constants for rapidly degradable materials, we can not reproduce the field sharp temperature increase after leachate injection. This could be explained by the possible existence of some aerobic degradation processes in the top layers of the waste accompanied by a higher release of energy and heat than the anaerobic phase, but existence of a one meter clay layer on the top of the landfill is in contrast with this assumption.

The same trend of decreasing and increasing of temperature with the same slopes for the numerical and in-situ curves are observed for T2. As showed in Fig. (3) at a depth of 2m, a hydraulic conductivity between 5.0E-4 and 1.0E-3 can be considered for the higher levels of the landfill which is confirmed also by different researchers (Lanini, 1998; Beaven et al., 1995; Hudson et al., 2001). Results show also that changes in hydraulic conductivity have more influence on the temperature results than changes in porosity. To completely validate these results more site data at different depths is needed.

5. Conclusion

The results of numerical simulation comparing to site data show that our model is able to reproduce the temperature changes in a bioreactor landfill during leachate recirculation due to changes in saturation. It makes it also possible to understand and explain the results of the site and evaluate some parameters which could not be exactly and directly identified in a bioreactor site, as hydraulic conductivity and porosity. We have observed that temperature of a landfill subjected to leachate recirculation is a sensitive function of the hydraulic conductivity of waste.

In the other hand, this model is not able to reproduce the large amount of heat production needed to rise the temperature as fast as in the field. It is also not able to reproduce the stationary condition which is observed on the site before leachate recirculation and it seems to be necessary to modify the heat production term and to consider a biological model of biomass and biogas production in the model.

So the next step of our research is to modify the heat and biogas production term and to validate the model by additional field and laboratory experiments. Sensitivity analyses are needed to define more precisely the important parameters of heat and biogas production to approach as more as possible to the field data.
6. References