NUMERICAL MODELING OF LANDFILL GAS PRODUCTION AND MIGRATION WITH A N_2-CO_2-CH_4-H_2O SYSTEM AND A PRODUCTION FUNCTION

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ABSTRACT

Biodegradation of the organic part of refuse disposed at landfills generates large quantities of methane and carbon dioxide, referred to as landfill gas. Most of the produced gas is emitted directly to the atmosphere while smaller quantities migrate beyond landfill boundaries through the adjacent soils. The numerical model TOUGH2-LGM was developed to simulate landfill gas production and migration processes within and beyond landfill boundaries. The model is derived from the original version of TOUGH2. TOUGH2-LGM has a new equation of state module and considers the migration of five components in partially saturated media: four fluid components (water, nitrogen, methane and carbon dioxide) and one energy component (heat). The four fluid components are present in both gas and liquid phases. The model incorporates gas-liquid partitioning of all of fluid components by means of dissolution and volatilization. Multiphase flow and heat transfer is described as in TOUGH2 whereas multi-component diffusion is an added capability. Landfill gas production is modeled as a simple exponentially decreasing function of time. The overall kinetic coefficient of landfill gas production was adjusted according to observed recovery rates in different age material. The numerical simulator was successfully used for modeling gas migration at two landfill sites: the Complexe environnemental de Saint-Michel (CESM) landfill at the City of Montreal and the St-Étienne-des-Grès landfill. The combination of field data and numerical simulations provides a good description of landfill gas production and migration mechanisms.

INTRODUCTION

Landfill gas can be viewed as a threat to safety and the environment that must be controlled but also as an energy resource. In either case, the production and migration mechanisms of landfill gas have to be well understood.

Landfills are complex systems in which many coupled processes take place: biodegradation of organic compounds, gas production and migration, leachate infiltration, heat production and transfer, ...

Numerical models can be used to provide a better fundamental understanding of landfill systems, and also as design tools for landfill gas recovery systems. The design and operation of these systems actually represent a very interesting engineering optimization problem. Landfill gas must no be allowed to migrate to the atmosphere or beyond landfill boundaries. On the other hand, gas recovery wells must not be pulled too hard to avoid the introduction of atmospheric oxygen within the refuse. Oxygen is lethal to anaerobic bacteria responsible for landfill gas production and stabilization of the organic matter.

We describe in this paper a numerical model representing the processes involved in landfill gas production and migration. The numerical model was developed from TOUGH2 (Pruess, 1987 and 1991).

LANDFILL GAS PROCESSES

Fresh organic materials, disposed along with other refuse components, supply the microbial inocula and form the necessary substrate for bacterial metabolism. As soon as refuse is placed in a landfill, two main biological transformation processes are initiated: *aerobic* and *anaerobic decomposition.* Both are controlled by microorganisms that transform and stabilize organic compounds towards simpler, mainly inorganic, substances (Farquhar and Rovers, 1973; McInerney and Bryant, 1981; Senior and Balba, 1987; Christensen and Kjeldsen,1989).

Initially, atmospheric air is trapped within the refuse, and bacterial decomposition occurs under aerobic conditions. This phase is characterized by a microbial activity in which labile molecules, such as simple sugars, are rapidly metabolized, while biodegradation of natural polymers (lignin, tannin) proceeds at a comparatively slower rate. A whole range of chemical intermediates along with a gas mixture of mostly CO_2 and NH_3 and significant amounts of water are generated in this phase. Heat is produced immediately after refuse placement and the temperature of the refuse is raised above the ambient temperature. However, the oxygen fraction of the trapped air is soon exhausted, and the long term decomposition is continued under anaerobic conditions.

If the moisture content is sufficiently high and a sufficient amount of microbial inocula is present, anaerobic digestion will start as soon as the oxygen gas fraction is depleted. Decomposition of the organic compounds is carried out by anaerobe microorganisms resulting in the production of methane and carbon dioxide as the two most reduced forms of carbon. For convenience, anaerobic microbial activity can be considered as a chain of continuous processes which proceed in several successive stages: *hydrolysis, acidogenesis, acetogenesis* and *methanogenesis.*

Many important physical processes accompany landfill gas production in landfills. Refuse is a partially saturated porous media in which multiphase flow of leachate and gas occurs. Gas migrates by advection under pressure gradients but also by diffusion of components under concentration gradients. Heat production and transfer is an important part of landfill gas production since most fluid properties vary with temperature.

We are mainly interested here by gas migration processes. As mentioned above, pressure and concentration gradients are the main factors causing gas movement. Gas generation increases the pressure and concentrations to which gases are submitted within the landfill. Gas migration, which is not necessarily proportional to the gas generation rate, will also be influenced by refuse properties. Since refuse is very heterogeneous, there will be a wide diversity of gas concentrations and pressures within different parts of the landfill. Once concentration and pressure gradients are established, landfill gas migrates vertically and laterally towards the low concentration and low pressure areas.

Landfill gas migration beyond landfill boundaries occurs in three basic directions: vertical emissions to the atmosphere, lateral migration to the adjacent soils, and dissolution and migration in the saturated zone.

LANDFILL GAS PRODUCTION MODEL

Following Monod's expression for a first-order reaction, the gas production rate Ω (m^3/tonne·year) can be approximated by an exponentially decreasing function of the initial gas production potential Π_o (m^3/tonne) and the overall kinetic rate constant k (s^{-1}) as follows:

$$\Omega = k\,\Pi_o\, e^{-kt}$$

This equation can be applied either globally to all the refuse or to refuse categories classified according to their respective biodegradability.

In order to completely define the gas production model, we have to determine the landfill gas production potential and the biodegradation rate. This can be accomplished by calibrating the coefficients of the gas production model according to the computed recovery rates at a given site. This is illustrated for the *Complexe environnemental de Saint-Michel* (*CESM*) landfill site in Montreal, Quebec.

Figure 1 shows the specific production rate in four different zones of the *CESM* in 1996. These zones have received refuse for various operation periods. The proportion of the total landfill gas production obtained from each zone was used to evaluate the recovery rate against the corresponding age. Besides zone 4, the manual fit of an exponential model through the data reproduces the change in production rate. Zone 4 is the active landilling area. In other zones, landfill gas recovery is estimated at least at 90% of the total production. It is believed that much more gas escapes however from zone 4. Landfilling operations require interruptions of the gas recovery system in this zone from time to time so gas recovery is reduced.

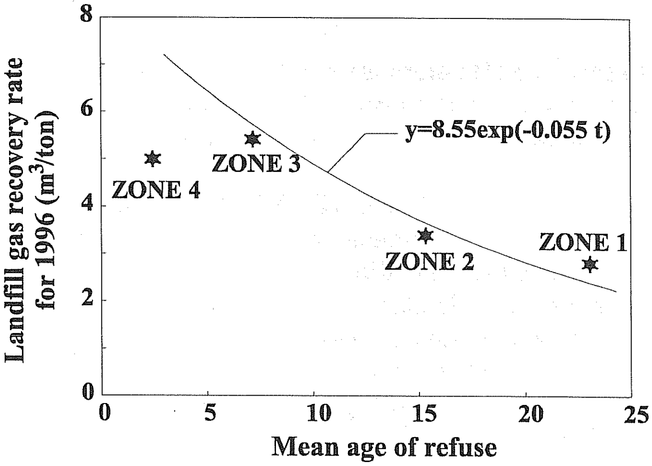

Figure 1. Landfill gas recovery rate for 1996 as a function of average refuse age in the four *CESM* landfill zones

Taking into account the assumed 90% gas recovery efficiency, the exponential fit in figure 1 implies an overall biodegradation coefficient *k* of 0.055 year^{-1} (or a half life $t_{1/2}$ of 12.6 years), an initial landfill gas potential Π_o of 172 m^3/tonne of refuse and an initial recovery rate Ω_o of 9.5 m^3/tonne·year. The average methane and carbon dioxide contributions are 55% and 45% of the recovered volume respectively. Methane production potential is thus 94.6 m^3/tonne of refuse.

This estimate of landfill gas production kinetics is based on a single point in time in 1996. In order to validate this estimate, the landfill gas production history is calculated based on the assumed kinetic constant and potential as well as the known refuse mass accumulation history and gas recovery at the site. Figure 2 shows predicted landfill gas production rate through time compared to the values obtained by previous studies and field data. Our prediction agrees quite well with the landfill gas production history available for the past few years.

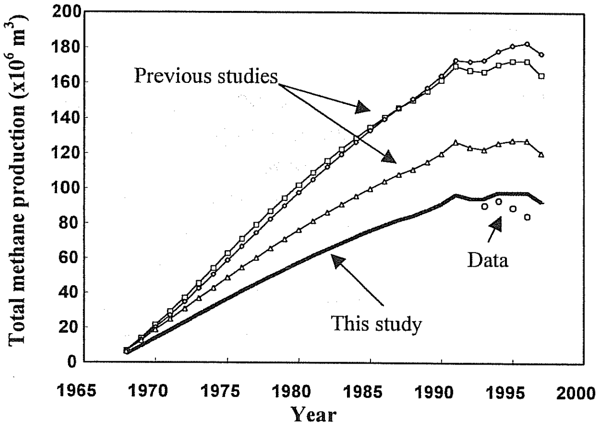

Figure 2. Total methane production through time as predicted by the production model compared to observed data and previous predictions

NUMERICAL MODEL DESCRIPTION

Numerical models have been developed to represent either landfill production or migration (Findikakis and Leckie, 1979; Mohsen et al., 1980; Metcalfe and Farquhar, 1987; El Fadel et al., 1989; Lang and Tchobanoglous, 1989). Some of these use rather complex landfill gas production models but most have shortcomings with respect to the representation of physical processes. Since physical processes control in large part the migration processes within and outside landfills, we have put more emphasis on developing an accurate representation of the physical processes. TOUGH2 was the ideal starting point to develop such a model. We used a practical approach with a simplified landfill gas production model that can be calibrated with field data.

Our numerical model, TOUGH2-LGM, has the following specifications:

1) Time dependent landfill gas production model;
2) Equation of state for a gas mixture of nitrogen, methane, carbon dioxide and water;
3) Advective and diffusive gas migration processes;
4) Multiphase flow of gas and liquid phases;
5) Exchanges of components between fluid phases;
6) Temperature effects on fluid properties and heat transfer processes.

The numerical model has evolved from a modified version of TOUGH2 (Lefebvre, 1995) used to model chemically reactive multiphase flow processes related to acid mine drainage production. Details on the numerical model are provided by Nastev (1998).

The central modification required to TOUGH2 is the development of a new equation of state module for a system with one energy component (heat) and four fluid components: N_2, CO_2, CH_4, and H_2O. Fluid components partition between the liquid and gas phase is controlled by temperature dependent Henry's law constants. The enthalpy of CO_2 and CH_4 dissolution in water is taken into account. This module also computes the viscosity of a gas mixture of these components as well as temperature dependent multi-component molecular diffusion coefficients. Effective diffusion coefficients in partially saturated porous media can be calculated with three different formula.

The other important addition required to the program is a subroutine representing the landfill gas production model to calculate the production rates of CH_4 and CO_2 as well as the accompanying heat generation. The overall anaerobic biodegradation reaction is exothermic and is assumed to produce 2528 kJ of heat per kg of CH_4 generated.

Five primary thermodynamic variables are needed to specify the state of the system. As in TOUGH2, the first variable is pressure and the last one is temperature. Again, similarly to TOUGH2, the second variable is either the "air" mass fraction for single phase conditions or water saturation (+10) for two phase conditions. The two additional primary variables are the mass fractions of CH_4 and CO_2 in "air" which is a mixture of N_2, CH_4 and CO_2. As in TOUGH2, the secondary parameters describing the properties of the fluid phases required for flux calculations are saturation, relative permeability, viscosity, density, specific enthalpy and capillary pressure. The same form of mass conservation as TOUGH2 is used to establish a set of simultaneous equations to be solved. The Newton-Raphson direct solver is used for that purpose.

The gas transport processes represented by the model were verified against one-dimensional, two-dimensional and radial analytical solutions.

THE *CESM* MODELS

The *Complexe environnemental de Saint-Michel* (*CESM*) landfill is operated by the city of Montreal. It is the third largest landfill in North America and has been in operation for almost 30 years. The landfill occupies a former limestone rock quarry. The refuse covers a 74 ha area and reaches a volume of 47 million m^3 with an average thickness of 64 m.

The leachate is pumped by a central well and monitored by a system of peripheral wells in the surrounding limestone. The landfill gas recovery system relies on more than 300 vertical collecting wells. An important network of peripheral monitoring wells is used to regulate the suction in the recovery system based on indications of lateral gas migration. This is very important since the landfill is located at the heart of a dense urban area. A large part of the landfill gas is sold to an onsite electric plant.

The *CESM* provides a unique opportunity to validate and apply the landfill gas numerical model. Important monitoring infrastructures and landfill cover test plots provide information on the physical conditions within the refuse and on gas production. The first application of these data was the calibration of the landfill gas production model discussed earlier. The first application of the numerical model uses a one dimensional grid to study the evolution of physical conditions through time within the refuse and the effect of variations in atmospheric pressure. The portion of refuse modeled is the unsaturated zone with a representative thickness of 40 m.

The model is run without gas recovery systems and shows the natural evolution of processes in the landfill. Figure 3 shows the pressure distribution through time within the refuse. Since gas production is at its peak in the earlier part of the landfill life, pressure builds up early to more than 3 kPa above atmospheric pressure (100 kPa used in the model). Pressure remains high in the first 20 years and decreases steadily thereafter. Temperature follows a similar pattern after reaching values beyond 35 °C.

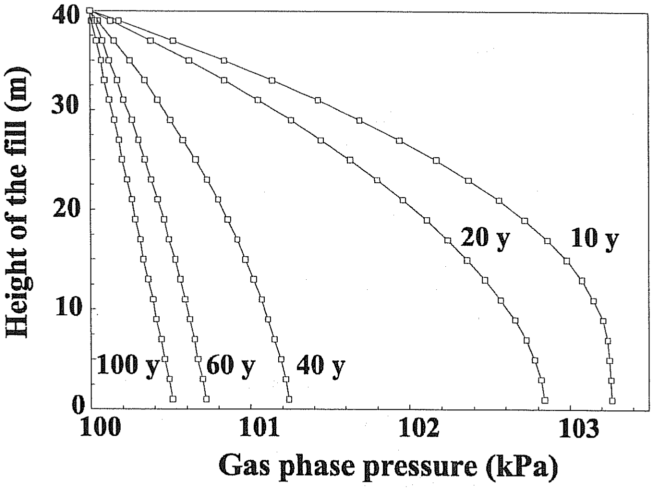

Figure 3. Pressure distribution through time as a function of depth for the one-dimensional model

Landfill gas production occurs for long periods. Even after gas production slows down, landfill gas has to be replaced by atmospheric gas. This is illustrated by figure 4. It shows the evolution in methane concentration through time at different depths within the landfill. In the early life of the landfill, a relatively even methane concentration is established. After production slows down (about 40 years), landfill gas pressure is reduced and landfill gas surface emissions are reduced. Under these conditions, diffusion of atmospheric air from the surface is no longer balanced by the outward gas flux, and methane concentration within the landfill is reduced steadily.

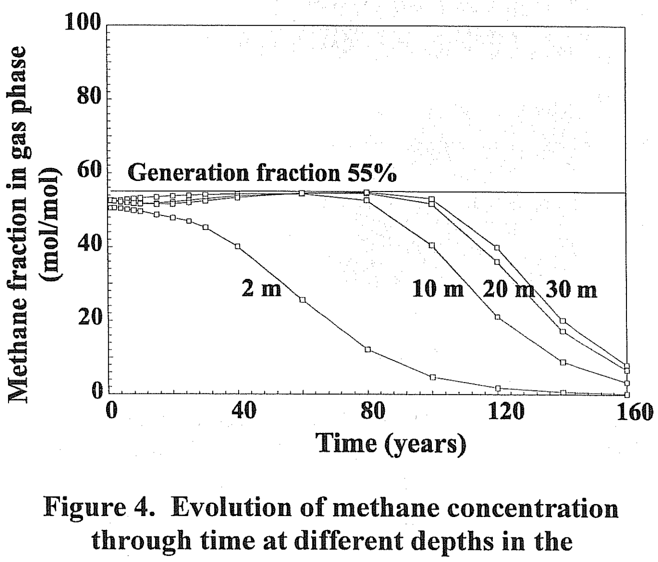

Figure 4. Evolution of methane concentration through time at different depths in the one-dimensional model

The concentration of methane in landfill gas is known to be highly variable through time. This goes against the fact that methane production ratios in landfill gas is supposed to be quite steady. Figure 5 provides part of the explanation for these fluctuating concentrations. This figure shows the changes in landfill gas concentration near the landfill surface when atmospheric pressure variations occur. It can be seen that the proportion of nitrogen (labeled "air") varies because of the barometric pumping effect. However, this effect is not alone responsible for the variations in methane concentration. The two main landfill gasses, methane and carbon dioxide, have quite different physical properties and behaviors. These properties affect their response to atmospheric pressure changes as shown in figure 5.

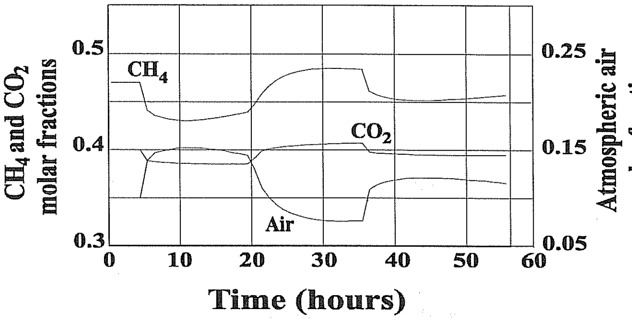

Figure 5. Changes in gas composition through time caused by variations in atmospheric pressure

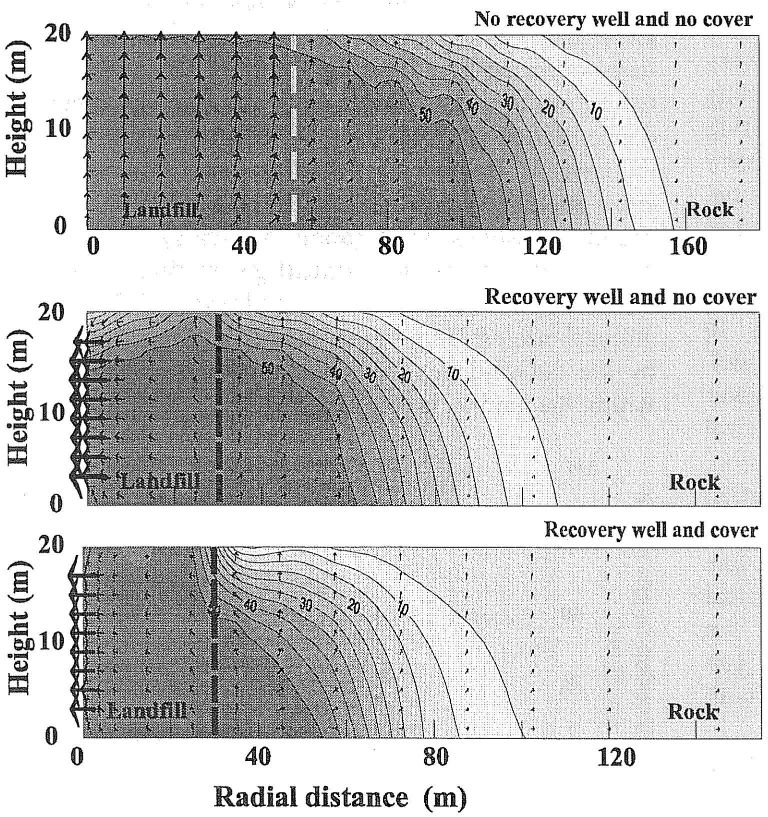

Figure 6. Predicted methane concentration and total flux at the limit of the landfill in contact with limestone bedrock for three model conditions: (Top) no cover layer and no gas recovery well; (Middle) no cover layer but with a gas recovery well; (Base) both with a cover layer and a gas recovery well.

Two-dimensional vertical sections were used to study landfill gas migration processes at the interface between refuse and the surrounding limestone rock. Figure 6 shows the concentrations and fluxes in methane for three cases in present day conditions. The case without recovery well shows that methane can migrate at great distances out of the refuse even in this low permeability material. The presence of a gas recovery well improves the situation. However, if such a well is at an important distance from the refuse limit or if the imposed suction is low, it cannot be operated efficiently to both limit landfill gas migration and prevent the entry of air in the refuse. The last case shows that the capping of refuse with a low permeability material prevents both the migration outside the refuse and the introduction of atmospheric air. The presence of a cover thus facilitates landfill gas recovery and the control of its migration.

THE SAINT-ÉTIENNE-DES-GRÈS MODEL

The second landfill site studied is at St-Étienne-des-Grès, Quebec. This landfill covers 39 ha with an average 12 m of refuse resting on the unsaturated zone of a sand.

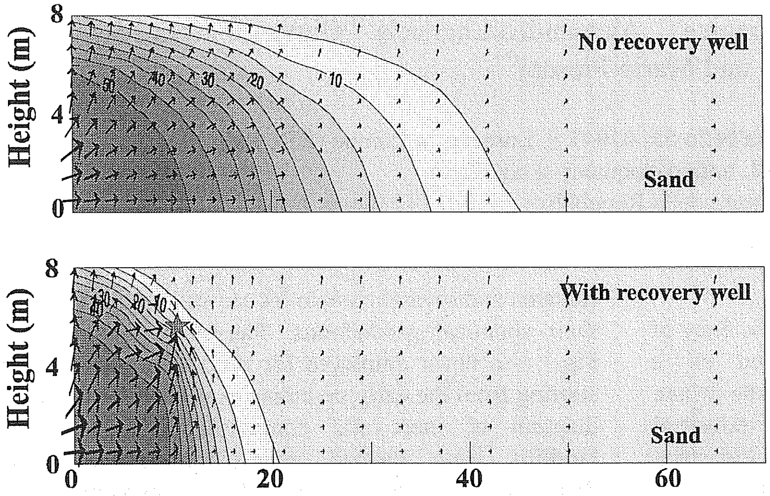

Figure 7. Predicted methane concentration away from the limit of the landfill in an unsaturated sand unit: (Top) without gas recovery system; (Base) with a horizontal gas recovery well.

At the site, landfill gas migration control is achieved by a peripheral horizontal well connected to a single pumping station. The modeling work was prompted by reports of gas concentrations observed in monitoring wells 10 m away from the landfill boundary close to the horizontal well. It appeared that the pumping system was insufficient to provide a vacuum in the entire length of the well.

Figure 7 (top) shows the conditions prevailing without a recovery well in the sand at the contact with the refuse as predicted by the model. As can be seen, methane migration at a concentration of 5% (the *lower explosive limit*) reaches as far as 40 m from the landfill boundary. The application of a small 0,5 kPa suction on the horizontal well is sufficient to prevent any migration of methane away from the landfill .

CONCLUSION

The numerical model developed is an efficient tool both to understand the fundamental mechanisms of landfill gas production and migration processes as well as to support the engineering design of gas recovery systems. TOUGH2 was a sound starting point to represent multiphase non isothermal landfill systems.

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