Transport Phenomena in the Conversion of an Anaerobic Landfill into an Aerobic Landfill

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Abstract: A two-dimensional dynamic model was developed using the concentrated reacting flow through porous media, heat transfer in porous media and mathematics interfaces. Initial aerobic biomass concentration was shown to be a very important parameter in the conversion of anaerobic landfills into aerobic landfills. Too low an initial aerobic concentration showed inefficient biodegradation whereas too high a concentration caused the biodegradation to proceed very quickly producing excess heat and killing the bacteria. Air flowrate was found to be less effective than leachate flowrate in controlling the landfill temperature. Increasing air flowrate by 4 times did little to change the temperature. The addition of leachate significantly cooled the waste.

Keywords: Bioreactor landfills, Anaerobic to aerobic conversion, transport phenomena

1. Introduction

The growing human population has led to the accumulation of municipal solid waste (MSW). This has necessitated the creation of more landfills. However, these landfills come at a cost, land. In the future, there will be no land available to devote to landfills and a viable solution needs to be implemented. A potential solution that is gaining ground is the bioreactor landfill.

Traditional "dry-tomb" landfills entomb the MSW in an attempt to prevent moisture from infiltrating the landfill lessening the environment for microbial growth and activity. Moisture infiltration can lead to many environmental problems such as the production of landfill gas (a very potent mixture of greenhouse gases) caused by microbial activity, production of toxic leachate, and production of noxious odours[1].

Bioreactor landfills are the opposite of dry-tomb landfills because moisture (and air for aerobic landfills) is injected into the landfill to promote microbial activity. These landfills are highly monitored and controlled to safeguard the environment and ensure efficient operation. The increased activity of the microbes in the MSW, increases the biodegradation rate, significantly decreasing the time required for waste stabilization.

Bioreactor landfills are split into two categories based on the dominant bacterial species present: anaerobic and aerobic. The type of bioreactor landfill has implications on the rate of biodegradation, composition of landfill gas and composition/toxicity of leachate. Experimental determination of the same information that a good model can provide, can take months or years, substantiating the need for a useful model to shorten the time considerably.

2. Governing Equations

2.1 Gas Flow Equation

Air is injected into the waste mass to supply oxygen to the aerobic bacteria. The bacteria produce gases, which are extracted along with any unconsumed oxygen (the gases are collectively called landfill gas). The flow of air and landfill gas is defined by the Brinkman equation:

$$\frac{\rho}{\phi_P}\left(\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\frac{\mathbf{u}}{\phi_P}\right)=\nabla\cdot\left[-P\mathbf{I}+\frac{\mu}{\phi_P}(\nabla\mathbf{u}+(\nabla\mathbf{u})^T)-\frac{2\mu}{3\phi_P}(\nabla\cdot\mathbf{u})\mathbf{I}\right] -\left(\frac{\mu}{\kappa}+\beta_F|\mathbf{u}|+\frac{Q_{br}}{\phi_P{}^2}\right)\mathbf{u} \quad (1)$$

Where ρ is the density of the gas (kg/m^3), $\mathbf{u}$ is the velocity vector (m/s), ϕ_P is the porosity of the waste (-), P is the pressure (Pa), μ is the viscosity of the gas (Pa·s), κ is the permeability of the waste (m^2), β_F is the Forcheimer coefficient (kg/m^4) and Q_{br} is the volumetric mass source (kg/m^3/s).

$$\frac{\partial(\phi_P\rho)}{\partial t}+\nabla\cdot(\rho\mathbf{u})=Q_{br} \quad (2)$$

2.2 Gas Transport Equations

The flow of the gas species is dependent on bulk flow (convection) and molecular flow (diffusion) processes. Since no one species makes up greater than 90% of the composition of the gas, transport of concentrated species is used:

$$\phi_P \rho \frac{\partial \omega_i}{\partial t} + \nabla \cdot \mathbf{j}_i + \rho(\mathbf{u} \cdot \nabla)\omega_i = R_i \tag{3}$$

Where ω_i is the mass fraction of component i (-), $\mathbf{j}_i$ is the mass flux vector relative to the mass averaged velocity (kg/m^2/s), R_i is the rate of consumption/production for component i (kg/m^3/s).

$$\mathbf{j}_i = -\left(\rho D_i^F \nabla \omega_i + \rho \omega_i D_i^F \frac{\nabla M_n}{M_n} \right) \tag{4}$$

Where D_i^F is the Fickian diffusion coefficient of component i (m^2/s) and M_n is the average molecular weight (kg/mol).

The multicomponent diffusion coefficients are found by the relationship proposed by Fairbanks and Wilke[2] using binary Fickian diffusion coefficients (found using the Chapman-Enskog equation).

$$D_i^F = \frac{1 - x_i}{\sum\limits_{j, j \neq i} \frac{x_j}{D_{ij}}} \tag{5}$$

Where D_{ij} is the binary Fickian diffusion coefficient of components i and j (m^2/s), x_i is the mole fraction of component i and x_j is the mole fraction of component j.

$$M_n = \left(\sum_i \frac{\omega_i}{M_i} \right)^{-1} \tag{6}$$

Where M_i is the molecular weight of component i (kg/mol).

$$\mathbf{N}_i = \mathbf{j}_i + \rho \mathbf{u} \omega_i \tag{7}$$

Where $\mathbf{N}_i$ is the combined mass flux vector of component i (kg/m^2/s).

2.3 Biokinetic Equations

Anaerobic biomass growth

Initially, when no oxygen is present, the dominant bacterial species are anaerobic. The equation describing the anaerobic biomass growth rate is as follows:

$$R_N = \frac{\partial X_N}{\partial t} = K_{M,N} \frac{S}{k_{s,N} + S} X_N - R_{D,N} \tag{8}$$

When the concentration of substrate (waste) is sufficiently high, $(S >> k_{s,N})$, simplifies Eq. 8 to:

$$R_N = \frac{\partial X_N}{\partial t} = K_{M,N} X_N - R_{D,N} \tag{9}$$

Where R_N is the anaerobic biomass growth rate (kg/m^3/day), X_N is the concentration of the anaerobic biomass (kg/m^3), $K_{M,N}$ is the anaerobic Monod maximum growth rate constant (day^{-1}), S is the available substrate (kg/m^3), $k_{s,N}$ is the substrate half-saturation constant for anaerobic growth (kg/m^3) and $R_{D,N}$ is the anaerobic biomass decay rate (kg/m^3/day).

Kim et al. assumed the decay rate of anaerobic biomass was given by the following[3]:

$$R_{D,N} = 0.05 K_{M,N} (X_N - X_{N,0}) \tag{10}$$

Where $X_{N,0}$ is the initial concentration of anaerobic biomass (kg/m^3).

Aerobic biomass growth

On the onset of aeration, the anaerobic bacteria begin to perish and aerobic bacteria begin to dominate. The equation describing the aerobic biomass growth rate is as follows:

$$R_A = \frac{\partial X_A}{\partial t} = K_{M,A} k_{temp} \frac{S}{k_{s,A} + S} \frac{c_{O_2}}{k_{O_2} + c_{O_2}} X_A - R_{D,A} \tag{11}$$

If the substrate concentration is sufficiently high, $(S >> k_{s,A})$, Eq. 11 reduces to:

$$R_A = K_{M,A} k_{temp} \frac{c_{O_2}}{k_{O_2} + c_{O_2}} X_A - R_{D,A} \tag{12}$$

Where R_A is the aerobic biomass production rate (kg/m^3/day), X_A is the concentration of the aerobic biomass (kg/m^3), $K_{M,A}$ is the aerobic Monod maximum growth rate constant (day^{-1}), k_{temp} is the temperature correction factor (-), c_{O_2} is the concentration of oxygen (kg/m^3), k_{O_2} is the oxygen half saturation constant (kg/m^3), $k_{s,A}$ is the substrate half-saturation constant for aerobic growth (kg/m^3) and $R_{D,A}$ is the aerobic biomass decay rate (kg/m^3/day).

Kim et al. assumed the decay rate of aerobic biomass was given by the following[3]:

$$R_{D,A} = 0.05 K_{M,A} (X_A - X_{A,0}) \tag{13}$$

Where $X_{A,0}$ is the initial concentration of anaerobic biomass (kg/m^3).

The temperature correction factor, shown in Eq. 14, describes the temperature dependence of the growth of aerobic bacteria:

$$k_{temp} = \frac{(T - T_{max})(T - T_{min})^2}{(T_{opt} - T_{min})\left[(T_{opt} - T_{min})(T - T_{opt}) - (T_{opt} - T_{max})(T_{opt} + T_{min} - 2T)\right]} \tag{14}$$

Where T is the temperature of the MSW (K), T_{max} is the maximum temperature for aerobic bacterial growth (K), T_{min} is the minimum temperature for aerobic bacterial growth (K) and T_{opt} is the optimal temperature for aerobic bacterial growth (K).

2.4 Species Consumption/Production Equations

Themelis and Kim proposed the following generalized reaction for the anaerobic biodegradation of waste[4]:

$$(C_6H_{10}O_4)_x + 1.5H_2O \rightarrow (C_6H_{10}O_4)_{x-1} + 3.25CH_4 + 2.75CO_2 \tag{15}$$

Based on this, the production of methane and carbon dioxide in the anaerobic state can be formulated:

$$\frac{R_{CO_2}}{2.75 \frac{M_{CO_2}}{M_{MSW}}} = \frac{R_N}{Y_{S/B,N}} = \frac{K_{M,N} X_N}{Y_{S/B,N}} \tag{16}$$

$$\frac{R_{CH_4}}{3.25 \frac{M_{CH_4}}{M_{MSW}}} = \frac{R_N}{Y_{S/B,N}} = \frac{K_{M,N} X_N}{Y_{S/B,N}} \tag{17}$$

Where R_{CO_2} is the production rate of carbon dioxide (kg/m^3/s), M_{CO_2} is the molecular weight of carbon dioxide (kg/mol), M_{MSW} is the molecular weight of MSW (kg/mol), M_{CH_4} is the molecular weight of methane (kg/mol), $Y_{S/B,N}$ is the substrate/anaerobic biomass yield coefficient (kg$_B$/kg$_S$) and R_{CH_4} is the production rate of methane (kg/m^3/s).

Themelis and Kim proposed the following generalized reaction for aerobic biodegradation of waste[4]:

$$(C_6H_{10}O_4)_x + 6.5O_2 \rightarrow (C_6H_{10}O_4)_{x-1} + 5H_2O + 6CO_2 \tag{18}$$

Based on this, the consumption of oxygen and production of carbon dioxide in the aerobic state can be formulated:

$$\frac{R_{O_2}}{-6.5 \frac{M_{O_2}}{M_{MSW}}} = \frac{R_A}{Y_{S/B,A}} = \frac{K_{M,A} \frac{c_{O_2}}{k_{O_2} + c_{O_2}} X_A}{Y_{S/B,A}} \tag{19}$$

$$\frac{R_{CO_2}}{6 \frac{M_{CO_2}}{M_{MSW}}} = \frac{R_A}{Y_{S/B,A}} = \frac{K_{M,A} \frac{c_{O_2}}{k_{O_2} + c_{O_2}} X_A}{Y_{S/B,A}} \tag{20}$$

Where R_{O_2} is the consumption rate of oxygen (kg/m^3/s), M_{O_2} is the molecular weight of oxygen (kg/mol), and $Y_{S/B,N}$ is the

Table 1: Physical Properties of Waste

Parameter	Unit	Value	Reference
Waste porosity (ϕ_p)	-	0.3	[5]
Waste permeability (κ)	m^2	10^{-12}	[5]
Waste density (ρ_{MSW})	kg/m^3	600	Assumed

Table 2: Biokinetic Parameters

Parameter	Unit	Value	Reference
Maximum anaerobic Monod growth rate constant $(K_{M,N})$	day^{-1}	0.2	[3]
Maximum aerobic Monod growth rate constant $(K_{M,A})$	day^{-1}	1.0	[3]
Oxygen half saturation constant (k_{O_2})	kg/m^3	$7x10^{-6}$	[6, 7]
Substrate/anaerobic biomass yield coefficient $(Y_{S/B,N})$	kg_B/kg_S	0.05	[3]
Substrate/aerobic biomass yield coefficient $(Y_{S/B,A})$	kg_B/kg_S	0.1	[8]
Minimum aerobic growth temperature $(T_{\min})$	°C	5	[6, 7, 9]
Optimal aerobic growth temperature (T_{opt})	°C	58.6	[6, 7, 9]
Maximum aerobic growth temperature $(T_{\max})$	°C	71.6	[6, 7, 9]

Table 3: Heat Parameters

Parameter	Unit	Value	Reference
Specific heat capacity of MSW $(C_{P,MSW})$	$MJ/m^3/K$	2.0	[10]
Heat conductivity of MSW (k_{MSW})	W/m/K	0.0445	[11]
Aerobic biodegradation heat of reaction (ΔH_{reac})	kJ/mol	-460	[3]
Leachate injection flowrate $(F_{L,in})$	L/day	2,100	[12]

substrate/aerobic biomass yield coefficient (kg_B/kg_S).

2.5 Energy Balance Equations

The source of heat is the aerobic biodegradation of the waste (exothermic reaction). Anaerobic biodegradation is slightly exothermic and can be endothermic depending on the composition of the waste. The energy balance is given by:

$$V(\rho C_P)_{eq}\frac{\partial T}{\partial t}+V\rho C_P\mathbf{u}\cdot\nabla T=\nabla\cdot(k_{eq}\nabla T)+Q \qquad (21)$$

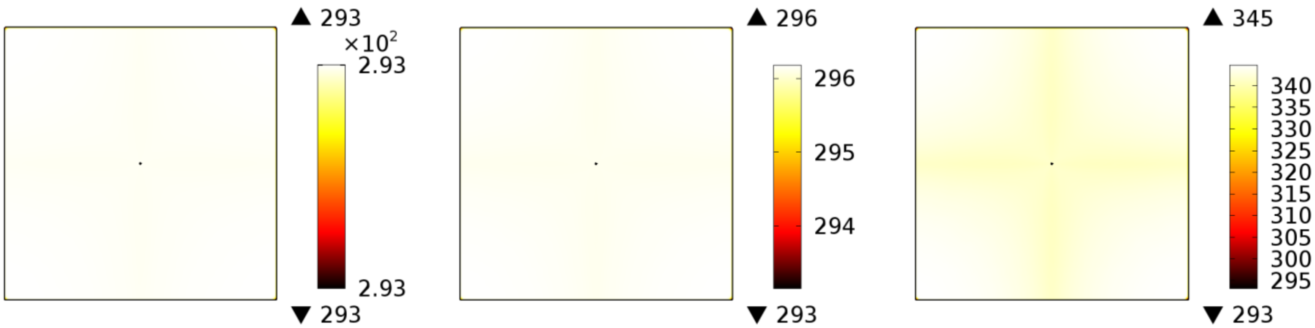
Where V is the volume of the MSW (m^3), k_{eq} is the equivalent thermal conductivity (W/m/K), C_p is the specific heat of the gas (J/kg/K) and Q is the source/sink term of energy (W).

$$(\rho C_P)_{eq}=\theta_{MSW}\rho_{MSW}C_{P,MSW}+(1-\theta_{MSW})\rho C_P \qquad (22)$$

Where θ_{MSW} is the mass fraction of the MSW (-), ρ_{MSW} is the density of MSW (kg/m^3) and $C_{P,MSW}$ is the specific heat of MSW (J/kg/K).

$$k_{eq}=\theta_{MSW}k_{MSW}+(1-\theta_{MSW})k \qquad (23)$$

Where k_{MSW} is the heat conductivity of the MSW (W/m/K) and k is the heat conductivity of the gas (W/m/K).



(a) 0.1 kg/m³ (b) 1 kg/m³ (c) 10 kg/m³

Fig. 1: Temperature after 1 day with varying initial aerobic biomass concentrations – initial temperature = 293K

$$Q = R\Delta H_{reac} - \rho_w F_{L,in} C_{p,w}(T - T_{L,0}) - \rho_g F_{g,in} C_p (T - T_{g,0}) \quad (24)$$

Where ΔH_{reac} is the reaction heat (kJ/mol), $F_{L,in}$ is the flowrate of leachate (mL/min), $C_{P,w}$ is the specific heat of water (J/kg/K), $T_{L,0}$ is the initial leachate temperature (K), $F_{g,in}$ is the flowrate of gas (L/min), and $T_{g,0}$ is the initial temperature of the gas (K).

3. Use of COMSOL Multiphysics

The model contains momentum, mass and energy transport phenomena. The momentum and mass balances are solved using the concentrated reacting flow in porous media interface. The energy balance was solved using the heat transfer in porous media interface. Due to the complex nature of the biokinetics involved in the process, COMSOL does not contain these equations by default. The equations had to be added using multiple distributed ODEs. COMSOL contained the option to couple the reacting flow in porous media and heat transfer in porous media interfaces. The biokinetics had to be coupled manually to both the reacting flow (gas consumption/production is dependent on biokinetics) and the heat transfer interfaces (reaction heat generation is dependent on biokinetics).

4. Analysis Conditions

Model parameters used in the various equations are found from published literature. The parameters describing the physical properties of the waste are found in Table 1. Kinetic parameters used for the model are found in Table 2. Heat transfer parameters are found in Table 3.

The geometry being used is a 20 m by 20 m cell (Figure 2). Air injection wells are located at the corners and the extraction well is located in the center.

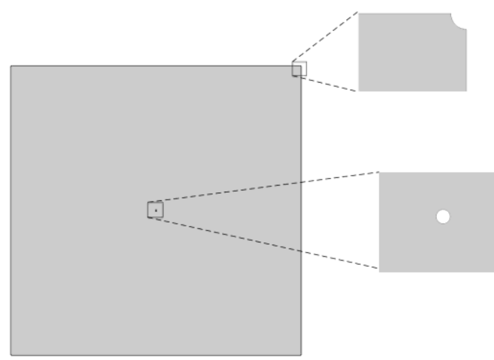
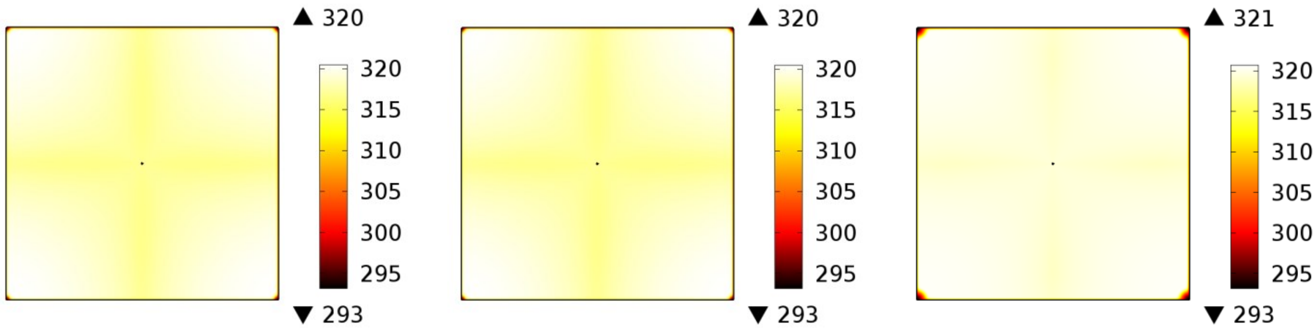


Fig. 2: Geometry of the landfill cell

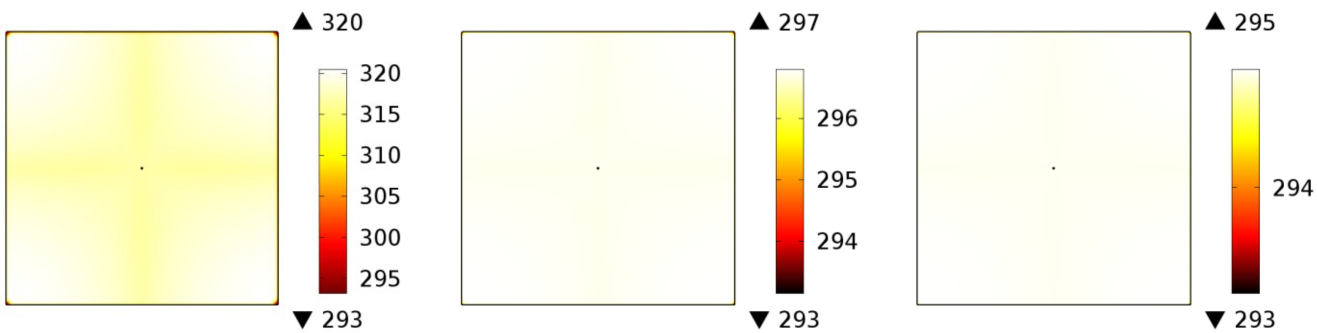
5. Results

Figure 1, shows the effect of initial aerobic biomass concentration on the conversion of anaerobic landfill into an aerobic landfill. Temperature is used as an indicator to give information about the biodegradation. Aerobic biodegradation is exothermic and the temperature can give insight into the efficacy of the biodegradation. For example, landfill temperatures remaining near ambient temperature indicate minimal aerobic biodegradation. Figure 1(a) shows a very small increase in temperature from the initial



(a) 10 scfm (b) 20 scfm (c) 40 scfm

Fig. 3: Temperature after 1 day with varying air flowrates – initial temperature = 293 K



(a) No leachate (b) 1050 L/day (c) 2100 L/day

Fig. 4: Temperature after 1 day with varying leachate injection rates – initial temperature = 293 K

temperature. This indicates inefficient biodegradation. At the other end of the spectrum is Figure 1(c). In this Figure, the temperature has increased rapidly, indicating the requirement for control of the biodegradation. Figure 1(c) shows the waste temperature nearing the maximum growth temperature shown in Table 2. Exceeding this temperature will cause the aerobic bacteria to die, and will significantly decrease the biodegradation rate.

As can be seen from Figure 1, if the landfill is left uncontrolled then the temperature will gradually climb. The temperature is generally controlled in two fashions: (1) by increasing the air flowrate or (2) by adding/increasing leachate injection.

Figure 3 shows the effect of increasing air flowrate. Increasing the air flowrate by 4 times, did little to decrease the temperature. Increasing the air flowrate, increases the distance the air gets into the waste before the air heats to the waste temperature. Another effect of the increase in air flowrate, is the homogenization of temperature via convection. The cell temperature becomes more uniform as the air injection flowrate increases.

However, as shown by Figure 4, the addition of leachate decreases the temperature significantly. The specific heat of leachate is approximately three orders of magnitude greater than the air. This shows that air is not effective in decreasing temperature and leachate is effective. This would require a significant increase in air flowrate to cool as effectively as leachate and would increase operating costs.

6. Conclusions

Initial aerobic biomass concentration was shown to be an important parameter in the conversion of an anaerobic landfill into an aerobic landfill. Too low of an initial aerobic biomass concentration and the growth of the aerobic biomass was slow. Too high of an initial aerobic biomass concentration and the growth of the aerobic biomass was rapid and produced excessive heat. Aerobic sludge can be injected to adjust the initial aerobic biomass concentration to quicken the conversion of the landfill.

The model has yet to be validated by experimental/industrial data. It is consistent with expectations and literature. The aerobic biomass grow with time and show a pattern of higher growth in areas of greater oxygen. This translates to higher oxygen consumption and carbon dioxide production in these areas.

Kinetic parameters have come from published literature and may not exactly fit the experimental conditions, therefore parameter fitting will likely be required.

This model can provide a very useful tool for the operation of aerobic landfills. Testing many different scenarios/conditions (e.g. different air flowrates, different air injection temperature, different ambient temperature) can be done in a relatively short time when compared to testing these scenarios experimentally. Scenarios that are not physically realizable may also be tested to see their effects on the landfill to provide additional insight.

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