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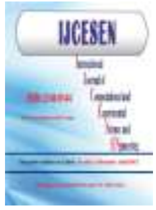

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Research Article

A Conceptual Framework for Biothermal variations in Municipal Solid Waste landfill under Mesophilic Temperature Regime

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Abstract:

Conversion of organic fraction of Municipal Solid Waste (MSW) into energy involves a complex biological and thermal reactions. This study presents a conceptual framework for biothermal variations in MSW landfill based on computational modelling. Landfill Mesophilic temperature range (291-321 K) was modelled using SOLIDWORKS simulation module based on steady state thermal analysis, and the biothermal variations obtained were graphically presented. The rate of heat generation in the landfill model varied in the range of 0.111-0.784 W/m3 at initial temperature distribution of 291 K to the range of 2.216-2.837 W/m3 at a terminal temperature distribution of 321 K. The landfill gas temperature varied in the range of 297-306 K at initial landfill temperature of 291 K to the range of 313-324 K at a terminal landfill temperature of 321 K. The aforementioned biothermal landfill variations revealed that, heat is a function of temperature upon which biogas evolve during anaerobic digestion. Furthermore, the total heat generated at the lower section of a landfill is higher than the total heat at the upper section of the system. With proper understanding of the biothermal variations in a landfill, heat energy and biogas can be harnessed for domestic and industrial purposes.

1. Introduction

Landfill is the most widely used and economically viable means of MSW disposal. The sustainable waste management concept of converting waste to energy makes landfill technology to be one of the most effective waste management methods. However, maximizing energy recovery from a given landfill is a function of several factors, of which temperature is one of such. MSW Landfills represent large energy reservoirs where large amount of biogas as well as heat energy are stored, provided its thermal properties are well characterized for optimum output [1]. Landfill temperature varies widely from one landfill to the other, and is affected by the size and height of the landfill, climatic conditions and landfilling operations as well as the type and age of waste deposited [2]. The temperature of waste in MSW landfills tends to increase gradually over time until a steady elevated temperature is reached generally within regions of the compacted waste mass. The temperature at which anaerobic digestion takes place can be classified under three categories namely: psychrophilic or cryophilic temperature (-20-15^{o}C), mesophilic temperature (18-55^{o}C) and thermophilic temperature (60^{o}C and above). Through pilot tests and experimental investigations, anaerobic digestion of organic substrates for energy recovery have been reported to be optimum within mesophilic temperature range [3, 4]. This is because thermophilic temperature is rarely obtained by natural decomposition process, except through artificial heating to increase the landfill temperature. Results obtained from studies on MSW landfills have been reported on the variations in thermal properties including elevated temperatures [5]. Yesiller et al. [6] measured landfill temperatures up to 60-90ºC in typical solid waste landfills under different climatic conditions across the world. In a landfill containing aluminium processing waste, landfill temperature of over 100ºC was reported from the gas wellheads [7]. Yesiller et al. [8] investigated the thermal process of municipal solid waste landfills as a function of operational conditions and climatic region. The heat generated values ranged from 23-77 MJ/m^3 without losses. Thermal gradients measured within the compacted waste stream was in the range of -30 and +22°C/m, with average absolute values less than 5°C/m. Steady elevated temperature of the landfill was in the range of 23 and 57°C while the peak heat content values ranged from 12.5 to 47.8°C/day. Yesiller et al. [9] understudied the heat management approaches in Municipal Solid Waste (MSW) landfills based on three strategies namely: extraction, regulation, and supplementation. For all strategies employed in the study, heat energy in the landfill was determined from the difference between temperature of the landfill waste and the temperatures targeted. Data obtained from landfill facilities with relatively low and high rate of heat generation revealed thermal energy ranging from -48.4 to 72.4 MJ/m^3 available for heat management. Maximum landfill temperature reported by Rees [10] varied from 40-65°C and were measured along one-third of the mid-section to over one-half depth of the landfill with total waste heights of approximately 20-60m. This is contrary to results reported by Koerner [11], where psychrophilic temperatures between 10 and 20°C were measured for wastes with maximum height of approximately 50m for over 9.5 years. Temperature variation towards the base of MSW landfill was reported between 30-50ºC [12, 13]. However, Rees [14] reported the optimum landfill temperature in England for gas production in the range of 40-45ºC. An experimental study conducted by Lamothe and Edgers [15] on the effects of environmental parameters on the laboratory compression of waste revealed that settlements increases with increasing temperatures. In a laboratory experiment, the range of optimum temperatures required for mesophilic and thermophilic microorganisms to thrive during waste decomposition process were identified as 35-40°C and 50-60°C [16, 17]. Onnen [18] investigated the thermal behaviour of vertical Heat Extraction Systems (HES) in Landfills using numerical models. The heat extraction rate ranged from 0-2550, 310-3080, and 0-530 W for the first year, peak year, and last year of the heat extraction process. Difference in baseline landfill temperatures and temperatures that are 0m away from the HES ranged from 5.2-43.2°C. An increase was observed in the total heat energy extracted at increasing waste filling rate. Wastes placed in warmer months resulted in an increase in the total heat energy extracted. In a bottom ash landfill, Klein et al. [19] found the energy released to be 250 MJ/m^3, resulting in 97℃ peak temperature. Nastev et al. [20] reported the rate of heat generated from MSW landfill as 40.2 kJ/mol of generated CH_4 and CO_2, and the minimum and maximum heat flux as 6.8×10^{-7} W/m^2 and 0.39 W/m^2. Several studies have been conducted on the bio-thermal variations of landfills. In this study, MSW landfill system was modelled using SOLIDWORKS 2018 version while the mesophilic temperature condition was computed using steady state thermal analysis in SOLIDWORKS flow simulation.

2. Materials and Methods

The 3D isometric landfill system was modelled using SOLIDWORKS 2018 software which is a solid modelling Computer Aided Design (CAD) as well as Computer Aided Engineering (CAE) tool that runs mainly on Microsoft Windows. The modelling steps started with 2D sketch, consisting of geometries such as arcs, points, conics, lines, splines and so on. Dimensions were added to the sketch to define the size and configuration of the geometry. Relations in the tool bar were used to define features such as parallelism, tangency, concentricity, perpendicularity among others. In the part assembly, sketches of individual parts were assembled together to form the intended solid model of the landfill system. The landfill data were obtained from a field prototype in the Faculty of Engineering, University of Benin, Nigeria. Materials used in the construction of the field prototype were used as a guide during selection of the landfill materials from SOLIDWORKS material library. A steady state thermal analysis was carried out to determine the biothermal behaviour of the landfill which was modelled as a closed system. This was done by clicking the simulation study tree in SOLIDWORKS thermal analysis module and selecting the steady state thermal analysis as the study type. The study properties were defined as presented in Table 1 and Table 2. Since biogas which is a combination of gases was not found in the material library, Apply/Edit material icon was clicked on the simulation study tree to add the biogas materials which were: 60% CH_4, 45.3% CO_2, 3% N_2, 1% H_2, 0.2% H_2O, 0.4% NH_3 and 0.1% H_2S. The gas percentage composition were obtained from the landfill prototype in the University of Benin. Applying the conditions in Table 1 and Table 2, the biothermal conditions specified for the landfill model was simulated to check its variations.

Table 1. *Parameters for the heat transfer simulation*

Type	Inlet volume flow
Faces	Face<7>@LID6-2
Flow parameters	Flow vectors direction: Normal to face Volume flow rate: 0.1000 m^3/s Mass flow rate: 0.020 kg/s Flow type: Inlet Mass Flow Viscous regime: Turbulent Turbulent intensity: 10% Turbulent length scale: 7% of the Hydraulic diameter Turbulent velocity scale: 5% of the free steam velocity
Thermodynamic parameters	Approximate pressure: 101325.00 Pa Mesophilic Temperature: 291-321 K
Internal materials	Biogas, MSW, Leachate
Ambient air pressure	0.101 MPa
Ambient temperature	294 K
Boundary conditions	Static pressure of 0.202 MPa at the start of each nozzles. The nozzles are 50 mm long, 20 mm wide lids at the start and then 10 mm openings at the end.
Mesh	Automatic, resolution 7.

As presented in Table 2, the following landfill gas parameters used by Orhorhoro et al. [21] and properties of the waste measured by Emmia et al. [22] were also considered in the thermal analysis carried out in this study. Temperature flow trajectory depicting the biothermal conditions at the upper and lower section of the landfill is presented in Figure 1. The landfill models as shown in Figure 2 and 3 incorporates all the functional materials needed for its operation. The gas extraction unit is modelled with four (4) cornered steel rods binned together with copper wire, and the annulus packed with granular materials (non-cancerous stone). Perforated gas extraction pipe is incorporated at the middle of the four (4) cornered steel rods to allow the flow and channelling of biogas generated from decomposing waste stream in the landfill to storage vessels. Borehole diameter for the gas extraction well is 0.20m while the gas extraction pipe diameter is 0.10m. The landfill model also incorporate perforated pipes buried horizontally (diameter of 0.10m and 0.40-50m spacing) within the compacted waste layers and also within the granular layers (gravel layer) at the bottom of the landfill. The purpose is for transporting and channelling of leachate to a sizable trench (leachate collection

Table 2. *Properties of the landfill phases*

Properties of the gas Phase	**Minimum**	**Maximum**
Pressure (Pa)	18781.47	507113.54
Thermal conductivity (W/mK)	0.015	0.038
Specific heat capacity (KJ/kgK)	600	2100
Density Fluid (kg/m^3)	0.282	0.840
Velocity (m/s)	0	2198.108
Velocity (X) (m/s)	-195.020	195.130
Velocity (Y) (m/s)	-28.893	2197.940
Velocity (Z) (m/s)	-201.483	202.130
Temperature (Fluid) (K)	280.96	330.20
Mach Number	0	7.23
Vorticity (1/s)	22.226	71927.174
Relative Pressure (Pa)	-82543.53	405788.54
Properties of Solid Phase (MSW)	**Minimum**	**Maximum**
Density (Kg/m^3)	5.2	9.8
Thermal conductivity (W/mK)	0.3	3.5
Specific heat capacity (KJ/kgK)	1000	2200
Properties of Solid Phase (leachate)	**Minimum**	**Maximum**
Density (Kg/m^3)	3.2	5.1
Thermal conductivity (W/mK)	0.200	0.600
Specific heat capacity (KJ/kgK)	1000	3000

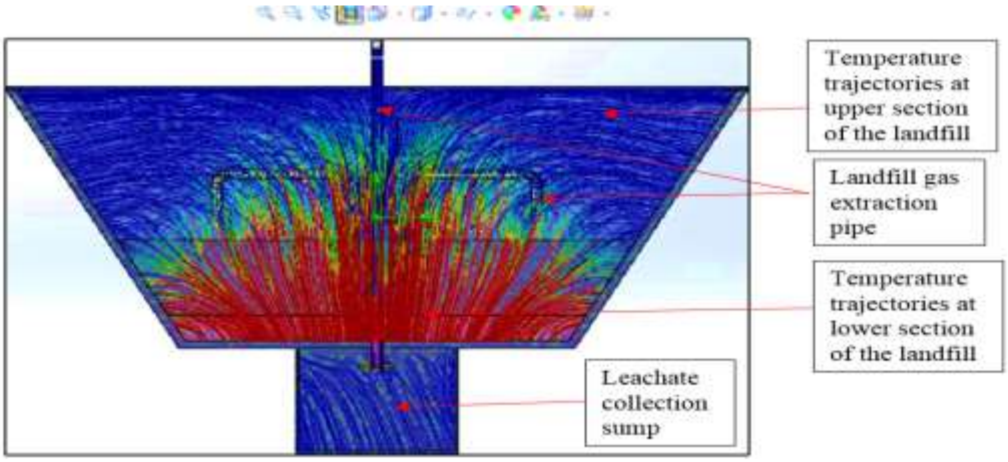

Figure 1. *Temperature trajectory depicting the biothermal conditions in the landfill*

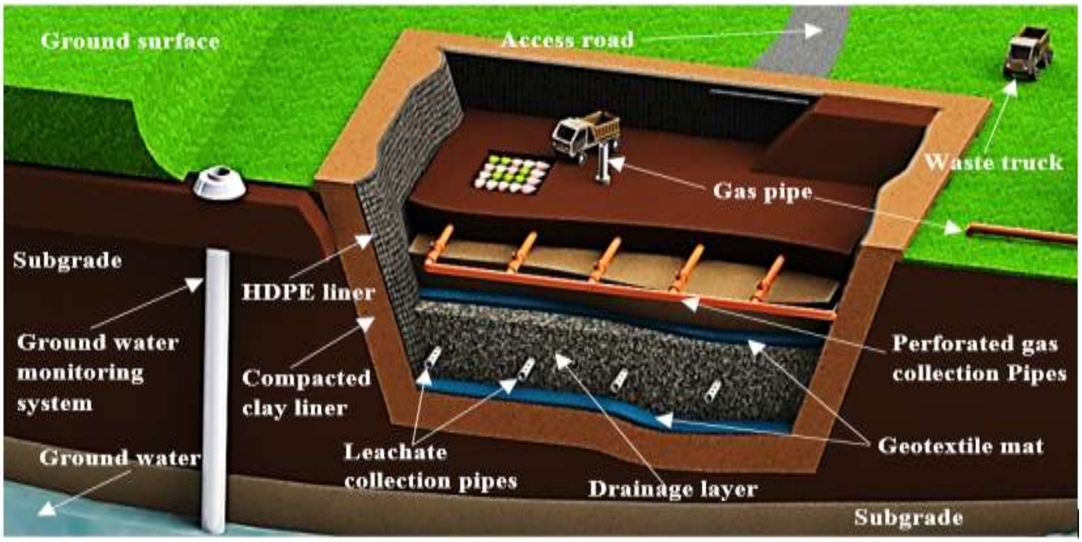

Figure 2. *Cross sectional view of the landfill showing internal components*

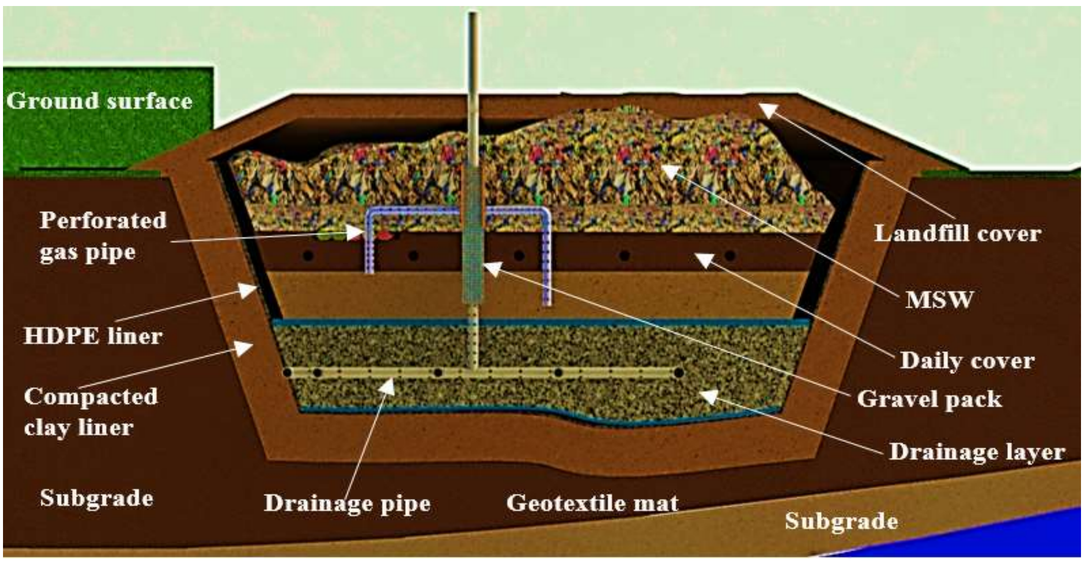

Figure 3. *Cross sectional view of the landfill with MSW inside*

(primary liner) is further modelled to align properly with the surface of the bentonite clay liner to further prolong water retention in the landfill. The HDPE material specification was thickness of 2mm as presented by Ikpe et al. [23]. The model also incorporates polypropylene geotextile mat or system sump) at a lower base of the landfill for extraction when necessary. The bottom and side walls of the is modelled with bentonite clay (secondary liner) of low hydraulic conductivity (1x10-7cm/s) to delay and control the rate of leachate percolation, while High Density Polyethylene (HDPE) liner geomembrane filter placed on the surface of the granular layer to separate solid particles from liquid content of the waste during decomposition. Specifications of this material as presented by Ikpe et al. [24] are melting point temperature of 30^{o}C, tensile strength between the range of 31.03-41.37MPa (ISO527), mass of 9613.75 g and thickness of 4.5mm. The waste permeability value was 3.x10-12m^2, porosity was 0.5, cover thickness was 0.3m, and the permeability of cover was 1x10-13m^2. In evens of the primary and secondary liner failure, ground water monitoring probes is also incorporated in the model to detect the presence of leachate in ground water. The above descriptions of the landfill models are presented in Figure 2 and 3. A method for determining the effect of temperature on landfill gas production is given by Equation 1 [18], while the temperature correction factor describing the temperature dependence of the growth of aerobic bacteria is given by Equation 2 [25].

$$k_{T_2} = k_{T_2} e^{\frac{E_\alpha (T_2 - T_1)}{R T_2 T_1}} \tag{1}$$

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

where k_{T_1} is CH_4 production rate at temperature 1, k_{T_1} is CH_4 production rate at temperature 2, E_α is the energy of activation, T is temperature and R is the ideal gas constant, where T is the temperature of the MSW, T_{max} denotes the maximum temperature for aerobic bacterial growth, T_{min} represents the minimum temperature for aerobic bacterial growth and T_{opt} denotes the optimal temperature for aerobic bacterial growth. Hanson et al. [26] modelled the waste heat generation using an exponential growth and decay function with time. The function is give by Equation 3.

$$HG = A \left(\frac{t}{B+t} \right) \left(\frac{C}{C+t} \right) e^{-\sqrt{\frac{t}{D}}} \tag{3}$$

where HG is the generation (W/m^3), T is the temperature (°C), t denotes time (days), A is the peak heat generation factor (W/m^3), B, C are the time factors (days and D denotes decay factor (days). Combining density, thermal conductivity, and heat capacity the equation for thermal diffusivity is given by Equation 4 [27, 28].

$$\alpha = \frac{k}{\rho c} \tag{4}$$

where α is the thermal diffusivity, k is the thermal conductivity, ρ is the density, c is the heat capacity. The thermal conductivity can be determined from the universal equation of heat flow given by Equation 5 [29].

$$\lambda_\Sigma = \lambda_s * \left\{ \frac{K}{[K * \varepsilon_s + (1 - \varepsilon_s)] * [\varepsilon_s + (1 - \varepsilon_s) * K]} \right\}^D * [\varepsilon_s + (1 - \varepsilon_s) * K] \tag{5}$$

where K is the proportionality factor λs is the thermal conductivity, D is dispersion state, ε_s volumetric fraction of the landfill. The three dimensional transient heat transfer equation is given by Equation 6 [27, 28].

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \dot{Q}_{hg} \tag{6}$$

Where T is the landfill temperature, t denotes time (days), α is the thermal diffusivity and $\dot{Q}_{hg}$ is the volumetric rate of heat generation. The equivalent heat conductivity is given as:

$$\lambda_{eq} = \phi \lambda_g + (1 - \phi) \lambda_s \tag{7}$$

where λ_s *is* heat conductivity of solid phase, λ_g is heat conductivity of gas phase, ϕ *is* the waste porous media. The equivalent heat capacity within a landfill system is given by Equation 8.

$$C_{eq} = \phi \rho_g c_{pg} + \rho_d c_{ps} \tag{8}$$

where c_{ps} is the specific heat capacity of solid phase, c_{pg} is the specific heat capacity of the phase. Heat capacity for the landfill surrounding soil is given by Equation 9 [30].

$$C_s \rho_s = C_m \rho_d + C_w \rho_d \frac{w_w}{100} \tag{9}$$

where C_s is the heat capacity of soil, ρ_s is the soil density, C_m is the heat capacity of mineral constituents, ρ_d is the dry soil density, C_w is the heat capacity of leachate, and w_w is moisture content. At any depth of the landfill, temperature can be determined at any time of the year using Equation 10 [31].

$$T_{z,t} = T_m + A_z\, Sin \left(\frac{2\pi t}{p} - z \sqrt{\frac{\pi}{\alpha p}} \right) \tag{10}$$

where $T_{z,t}$ is the temperature at depth at different landfill depth z and time t, T_m is the mean annual earth temperature, A_z is the temperature amplitude at depth, z is the depth beneath ground surface, α is the soil thermal diffusivity. The waste volumetric heat capacity is given by Equation 11 [32].

$$C_w \sum_{i=1}^{n} x_i (C_i) \quad (11)$$

where C_w is the volumetric heat capacity of waste. However, the heat capacity of buried waste can be determined using Equation 12.

$$C_{p.s} = x_{msw}\left[(1-\varphi)\sum_{i=1}^{n} C_{p,i}x_i + \varphi C_{p,H_2O}\right] + x_{ash}C_{p,ash} \quad (12)$$

where $C_{p,s}$, $C_{p,i}$, and $C_{p,ash}$ are the heat capacities of buried waste, i is the biodegradable component in wet refuse, and ash, and φ is the moisture content. Using the analytical formulation for ground temperature, the baseline waste temperatures can be determined as [33]:

$$T_{(x,t)} = T_m - A_s e^{-x\sqrt{\pi/365\alpha}} \operatorname{Cos}\left[\frac{2\pi}{365}\left(t - t_o - \frac{x}{2}\sqrt{\frac{365}{\pi\alpha}}\right)\right] \quad (13)$$

where $T_{(x,t)}$ is the temperature at depth x and time t, T_m is the mean annual earth temperature, A_s is the amplitude of surface temperature wave x is the depth below the landfill surface, t is the time of the year in days and t_o is the phase constant. Ground temperature in the vicinity of the landfill due to constant heat rate in polar coordinate is given by Equation 14.

$$\theta(r,t) - \theta_0 = \frac{q_l}{4\pi k}\int_{\frac{r^2}{4\alpha t}}^{0} \frac{e^{-u}}{u} du \quad (14)$$

where θ_0 is the ground initial temperature, q_l is the heat rate per length of the landfill, k is the thermal conductivity and α is the thermal diffusivity of the ground. Based on the finite-line source theory, Zeng et al. [34] proposed the analytical equation for temperature response in the ground as:

$$\theta(r,z,t) - \theta_0 = \frac{q_l}{4\pi k}\int_0^H \frac{\operatorname{erfc}\left(\frac{\sqrt{r^2+(z-h)^2}}{2\sqrt{\alpha t}}\right)}{\sqrt{r^2+(z-h)^2}} - \frac{\operatorname{erfc}\left(\frac{\sqrt{r^2+(z+h)^2}}{2\sqrt{\alpha t}}\right)}{\sqrt{r^2+(z+h)^2}} dh \quad (15)$$

where H is the depth and erfc is complementary error function. Municipal solid waste is a porous medium with pore spaces between irregularly shaped solid grains. Analytical equations applicable to heat conduction in porous media is given by Equation 16 [35].

$$\begin{cases} (1-\emptyset)\rho_s c_s \frac{\partial\theta_s}{\partial t} = (1-\emptyset)\nabla.\ (k_s\nabla\theta_s) \\ \quad +(1-\emptyset)Q_s + h(\theta_f - \theta_s) \\ \emptyset\rho_f c_f \frac{\partial\theta_f}{\partial t} + (\rho_f c_f)q_f.\nabla\theta_f = \emptyset\nabla.(k_f\nabla\theta_f) \\ \quad +(1-\emptyset)Q_f + h(\theta_s - \theta_f) \end{cases} \quad (16)$$

where θ_s and θ_f are the solid and fluid temperatures, ρ_s and ρ_f are the densities of solid and liquid phases c_s and c_f are specific heat capacities of solid and liquid phases, k_s and k_f are heat conductivities, Q_s and Q_f are sources for liquid phases, $\emptyset$ is the landfill waste porosity and h is the exchange heat transfer coefficient. However, the constitutive equations for heat transfer in porous media is given by Equation 17 [36].

$$\begin{cases} (1-\emptyset)\rho_s c_s \frac{\partial\theta_s}{\partial t} = (1-\emptyset)k_s\nabla^2\theta_s + h(\theta_f - \theta_s) + (1-\emptyset)Q_s \\ \emptyset\rho_f c_f \frac{\partial\theta_f}{\partial t} + \rho_f c_f q_f\ \nabla\theta_f = \emptyset k_f\nabla^2\theta_f - h(\theta_f - \theta_s) + \emptyset Q_f \end{cases} \quad (17)$$

3. Results and Discussion

written SOLIDWORKS flow simulation was used to simulate the internal condition of the landfill system based on mesophilic temperature ranging from 291-321K. Figure 4 shows the flow trajectory of mesophilic temperature distribution within the landfill system. However, Figures 5a-f are graphical representation of mesophilic temperature distribution between 291 and 321 K across the landfill system. The temperature flow trajectory within the landfill system is a function of heat transfer across the entire system as shown in Figure 4. In the hydrolysis phase of anaerobic digestion in the landfill, carbohydrates, fats and proteins are broken down by microorganisms into simple sugars and fatty acids. The products of hydrolysis are broken down into carbonic acids, alcohol, hydrogen, carbon dioxide and ammonia in the acidogenesis phase, while the products of acidogenesis are further broken down into hydrogen, acetic acid and carbon dioxide in the acetogenesis phase. In the methanogenesis phase, the products of acetogenesis are broken down by methanogenic bacteria into biogas which primarily consists of methane and carbon dioxide. The chemical reactions taking place through the aforementioned anaerobic digestion of organic fraction of MSW in a landfill generally have three by-products namely: solid which is the digestates left after decomposition, liquid which is the leachate generated from the process and gas which is the biogas that is processed into bio-methane. Obtaining the bi-products is a function of some parameters, particularly temperature which enable microbes present in the system to thrive and effective breakdown organic fraction of the waste. This is because, increases in the landfill temperature stimulate gas particle movement, tending also to increase the gas pressure, so that landfill gas spreads more quickly.

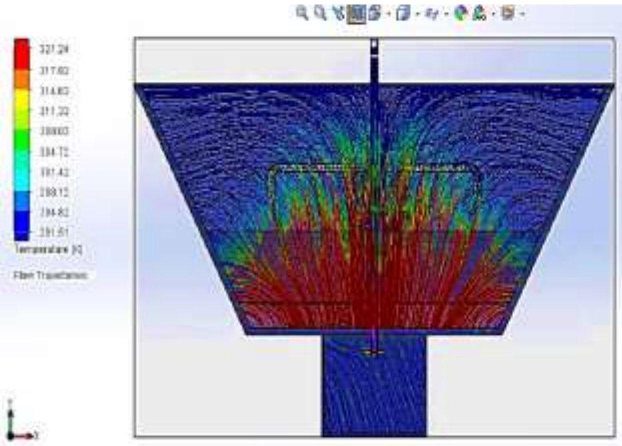

Figure 4. *Trajectory of mesophilic temperature distribution within the landfill*

Landfill temperature which takes the form of heat begins to flow gradually as decomposition takes place in the landfill. The heat which is a function of organic waste decomposition and landfill temperature begins to flow from a region of higher temperature to a region of lower temperature inside the landfill. Depending on the landfill temperature, the initial heat transfer inside the landfill may not have a wide range of coverage, thus resulting in a non-uniform temperature profile represented as scattered plot in Figures 5a and Figure 5b. This usually takes place during hydrolysis phase or the initial time when waste is newly placed in the landfill. At this stage, the necessary chemical reactions, microbial activities, as well as waste decomposition is not fully developed. After these phases shown in Figure 5a and Figure 5b, the heat distribution continues through acidogenesis phase until a constant temperature is attained within the landfill system where further decomposition of organic feedstock will cause further generation, distribution and increase (in acetogenesis phase) in the landfill temperature as shown in Figures 5c-e respectively. When all operating conditions are fully developed and well established, further increase or decrease is no longer observed in the landfill temperature. This phase of anaerobic digestion in the landfill is referred to as stabilization phase, a process where all operating conditions (temperature, available nutrients, Potential of Hydrogen-pH, water content, C/N ratio etc.) have stabilized and the system performs optimally. Under such condition, the landfill will produce gas at a steady rate for as long as the condition remains optimally constant. It is important to note that waste materials in the landfill serves as food for the microorganisms while the nutrients present in the waste serves as supplements needed for their growth. After a long term operation of the landfill, nutrient availability in the waste begins to deplete due to the long term consumption/decomposition by microorganisms. This has a direct effect on the landfill performance, as microbial activities will reduce as a result of insufficient waste food or nutrient for microbes to feed on and maintain the anaerobic condition of the system. At this stage, a decline is likely to be observed in the biogas yield, landfill temperature and pressure. This is graphically represented in Figure 5f, where the trend in landfill temperature is gradually decreasing, thus, having a negative effect on the landfill operating conditions. The variations in heat generation rate at each mesophilic temperature used in this investigation are presented

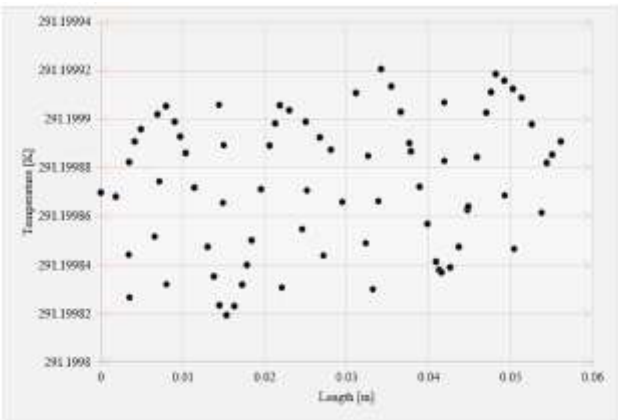

Figure 5a. *Temperature distribution at 291 K across the landfill system*

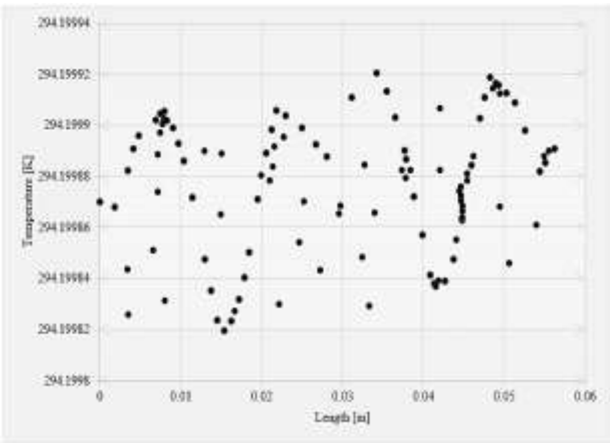

Figure 5b. *Temperature distribution at 294 K across the landfill system*

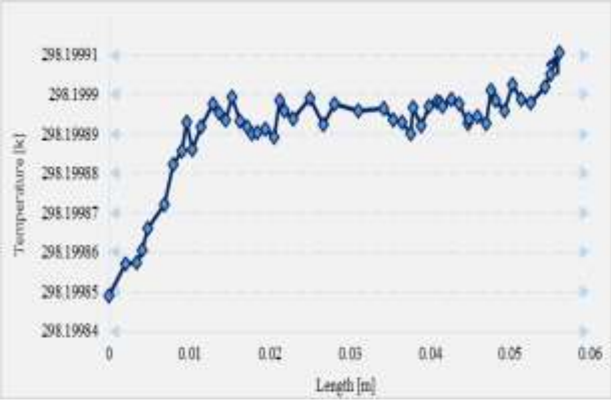

Figure 5c. *Temperature distribution at 298 K across the Landfill System*

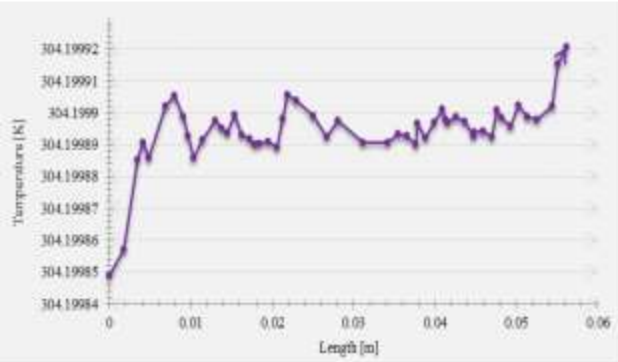

Figure 5d. *Temperature distribution at 304 K across the landfill system*

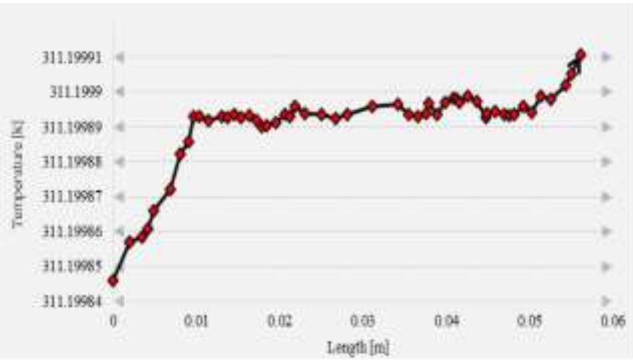

Figure 5e. *Temperature distribution at 311 K across the landfill system*

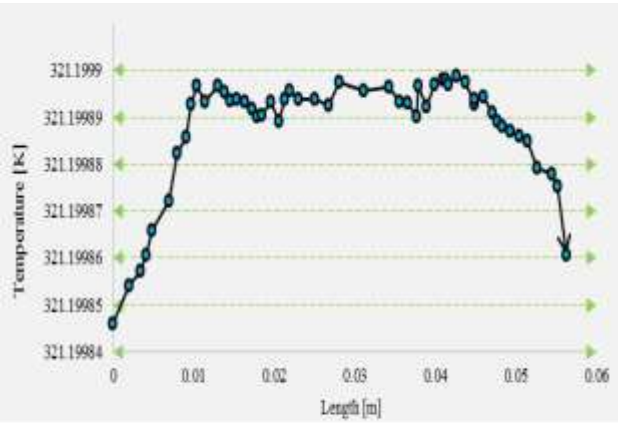

Figure 5f. *Temperature distribution at 321 K across the landfill system*

in Figures 6a-f. At landfill temperature of 291K, the rate of heat generation in the system varied from 0.111-0.784 as shown in Figure 6a, at landfill temperature of 294K, the rate of heat generation in the system varied from 0.301-0.974 as shown in Figure 6b. Furthermore, at landfill temperature of 298K, the rate of heat generation in the system varied from 0.813-1.485 as shown in Figure 6c, at landfill temperature of 304K, the rate of heat generation in the system varied from 1.320-1.892 as shown in Figure 6d. Moreover, at landfill temperature of 311K, the rate of heat generation in the system varied from 1.714-2.387 as shown in Figure 6e, at landfill temperature of 321K, the rate of heat generation in the system varied from 2.216-2.854 as shown in Figure 6f. There is correlation between the aforementioned values obtained for heat generation rate in this study and that of Emmia et al. [22], Hanson et al. [26], Magyar [29], Hanson et al. [37] and Nocko et al. [38]. The variations in heat rate is observed to increase as the temperature condition increases. It can be observed in the heat transfer trajectories that higher heat values tends to be at the lower section of the landfill profile while lower heat values are observed at the upper section of the landfill. This is because when waste is placed in the landfill cells, there is oxygen starvation, increased moisture content and increased heat at the bottom part of the landfill than the upper part. Reason being that, waste materials in the landfill are highly compacted/compressed, during which all possible voids are filled up and pore spaces eliminated, leaving the base of the landfill with little or air. Furthermore, water contents present in the waste materials flow downward under gravity to the bottom of the landfill. Since the landfill is conditioned for anaerobic digestion, the anaerobes which are poisoned by air migrates to the bottom of the system. The high concentration of anaerobic microorganisms at the lower part of the system causes increase in microbial activities, thereby, increasing the rate of heat generated at the lower section of the system than the upper section. This is indicated by red colour and also by the heat values, that variations in the rate of heat generation and distribution is higher at the lower section of the landfill profile (see Figure 6a-f), than the upper section. It is important to note that, heat variation in the landfill is directly proportional to the temperature of the landfill. Therefore, if there is a reduction in the rate of heat generation and distribution at any part of the landfill, the temperature in that part of the system may decline as well. Figures 7a-f are graphical representation of landfill gas temperature variation at landfill temperature ranging from 291-321 K.

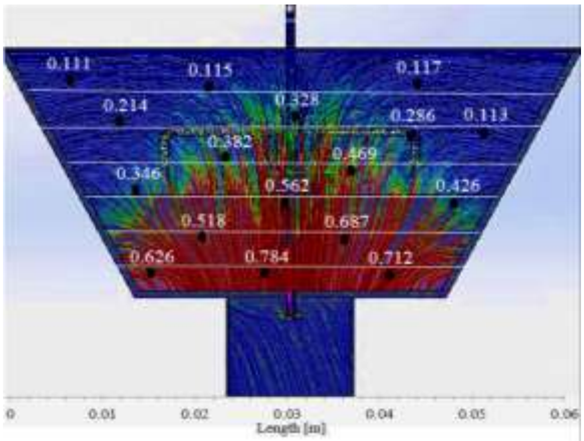

Figure 6a. Variation in landfill heat rate*(W/m^3) at temperature distribution of 291 K*

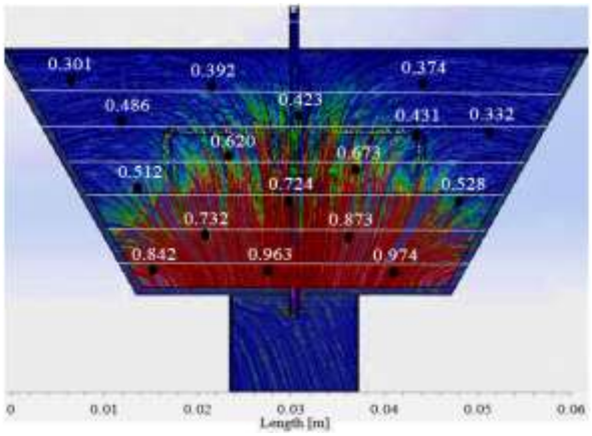

Figure 6b. *Variation in landfill heat rate(W/m^3) at temperature distribution of 294 K*

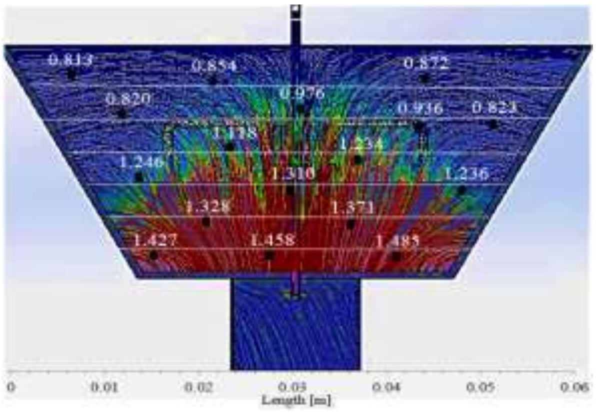

Figure 6c. *Variation in landfill heat rate (W/m^3) at temperature distribution of 298 K*

The trend in the landfill gas temperature plots is sinusoidal, implying that the landfill gas temperature inside the system increases and decreases at the same time. This is because, of the variations in microbial activities inside the landfill. As discussed earlier in the case of heat generation and distribution rate, the heat concentrates highly in areas with highest microbial activities, and so does the peak temperatures and biogas evolving from the landfill

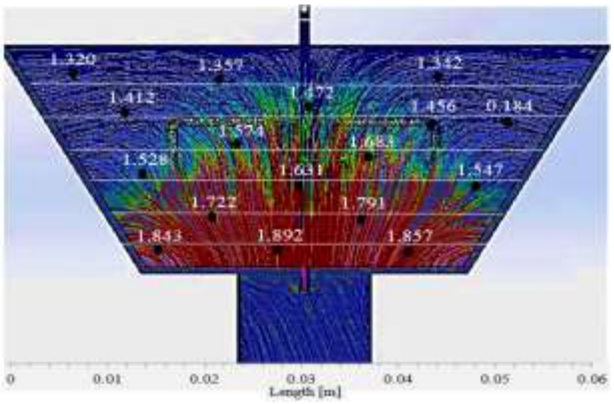

Figure 6d. *Variation in landfill heat rate (W/m^3) at temperature distribution of 304 K*

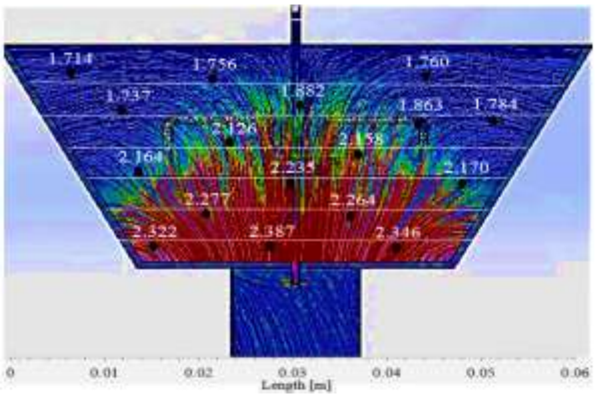

Figure 6e. *Variation in landfill heat rate (W/m^3) at temperature distribution of 311 K*

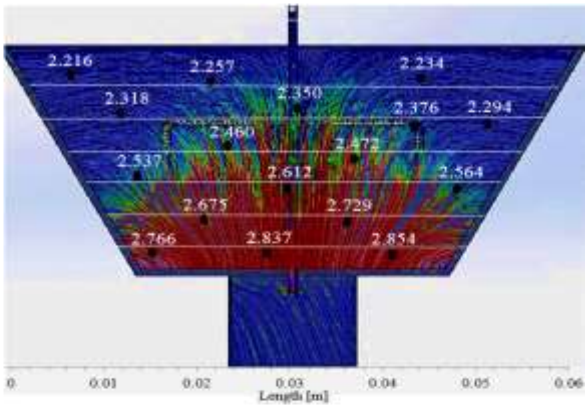

Figure 6f. *Variation in landfill heat rate (W/m^3) at temperature distribution of 321 K*

process areas or cells. That is the reason why some landfill cells produce higher biogas yield than other cells in the same landfill. It can be observed in Figures 7a-f, that the landfill gas temperature variation at the lower section of the landfill appears to be the peak gas temperature values, while the landfill gas temperature variation at the upper section of the landfill tends to be the minimum gas temperature values. Generally, gas flows from a region of higher concentration to the region of lower concentration within the boundaries of a system. In this case, the landfill gas flows from the landfill compacted waste mass at the lower section of the system to the upper part (known as gas holder) where gas concentration is lowest. During this process, temperature of the gas at the time it leaves the lower section of the landfill decreases gradually as it flows towards the upper section where there are no microbial activities. This implies that the landfill gas temperature decreases as the gas flows upward towards the landfill cover. This also applies to the landfill gas temperature flowing through the gas extraction pipes laid within the compacted waste mass, as the temperature around the gas extraction point reduces to some extent during extraction. Temperature of the final extracted landfill gas is the difference between the landfill gas temperature at the upper and lower section of the landfill system.

4. Conclusion

Investigation of this type generally requires the design and construction of at least a prototype landfill, where the necessary data required for further development is obtained. In recent times, Computer aided tools have been employed in three dimensional modelling and simulation of a landfill and its biothermal process. The mesophilic temperature conditions and biothermal variations in MSW landfill was successfully modelled in this study using SOLIDWORKS heat simulation module.

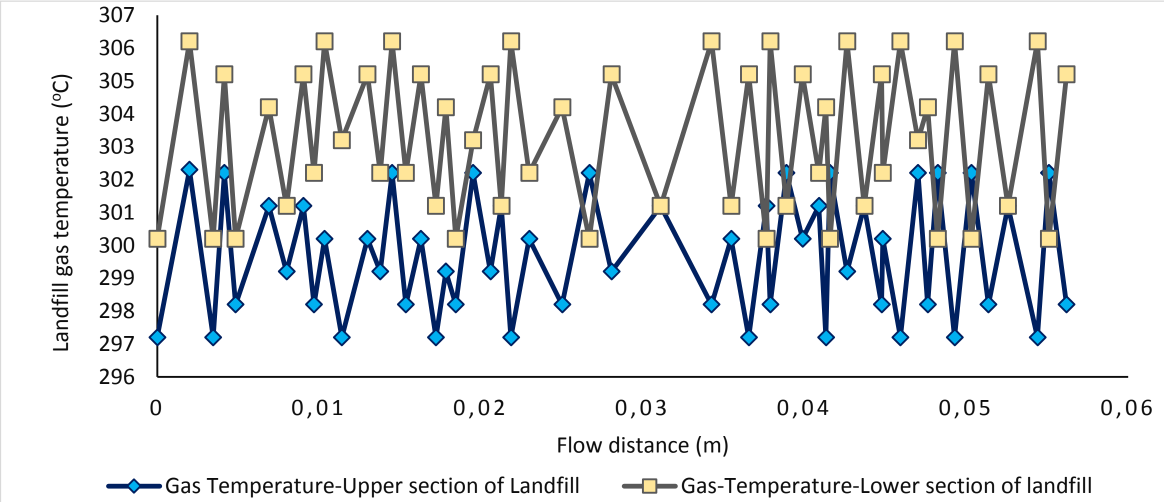

Figure 7a. *Landfill gas temperature variation at landfill temperature of 291 K*

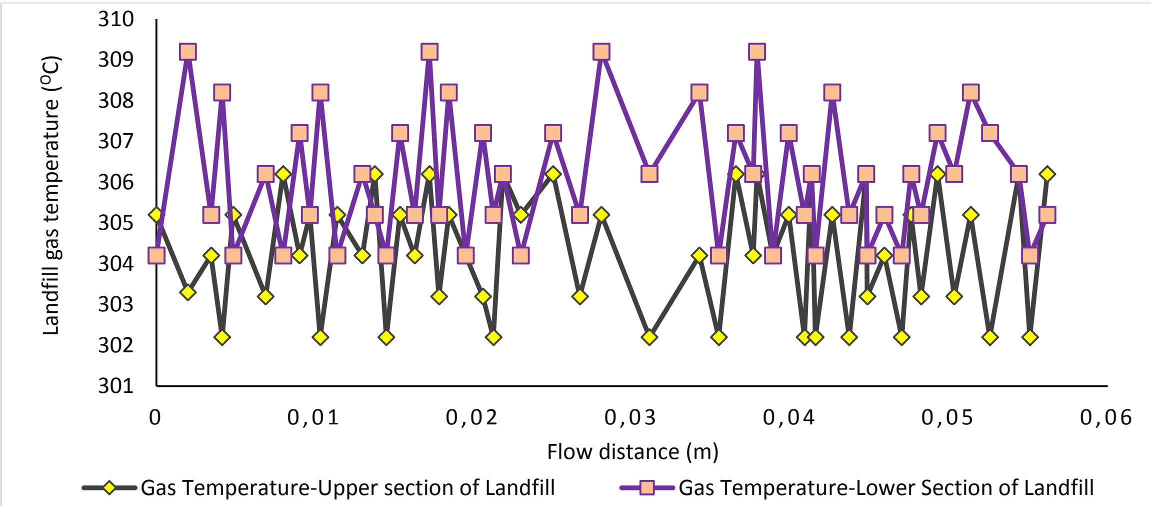

Figure 7b. *Landfill gas temperature variation at landfill temperature of 294K*

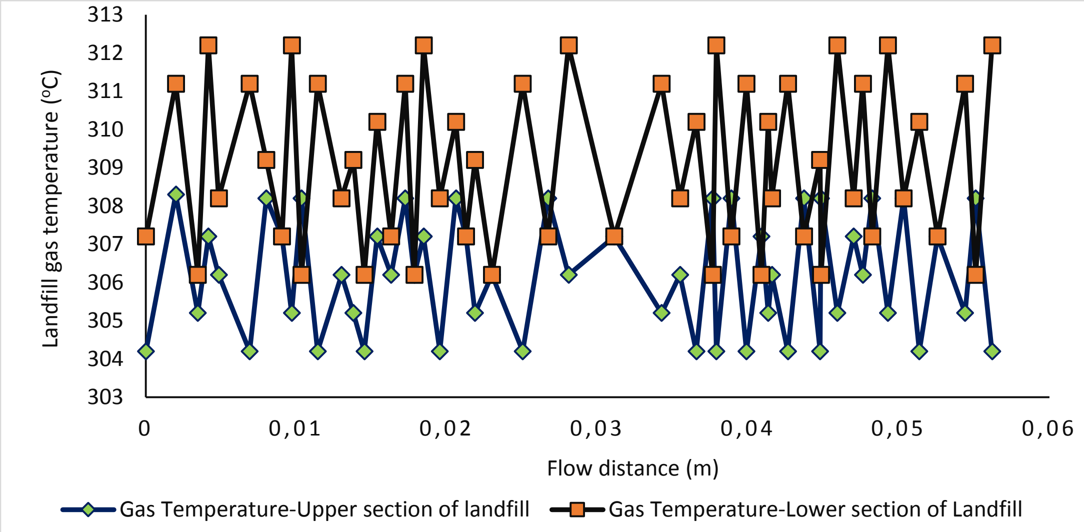

Figure 7c. *Landfill gas temperature variation at landfill temperature of 298K*

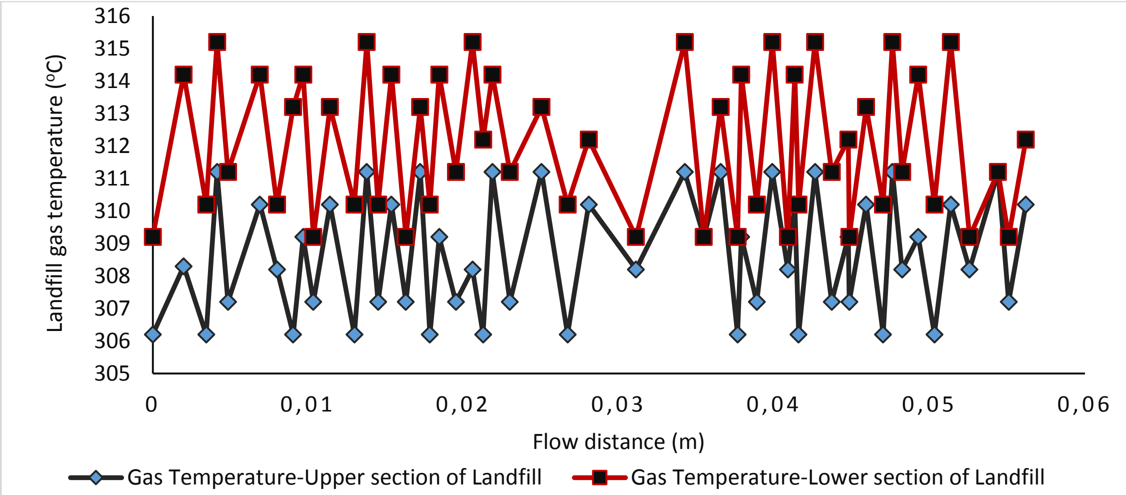

Figure 7d. *Landfill gas temperature variation at landfill temperature of 304 K*

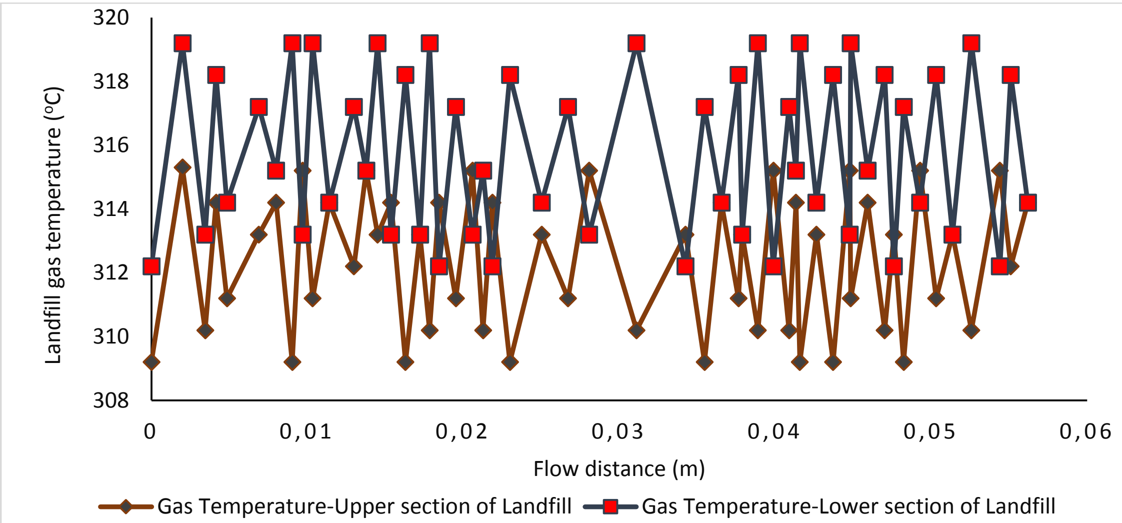

Figure 7e. *Landfill gas temperature variation at landfill temperature of 311 K*

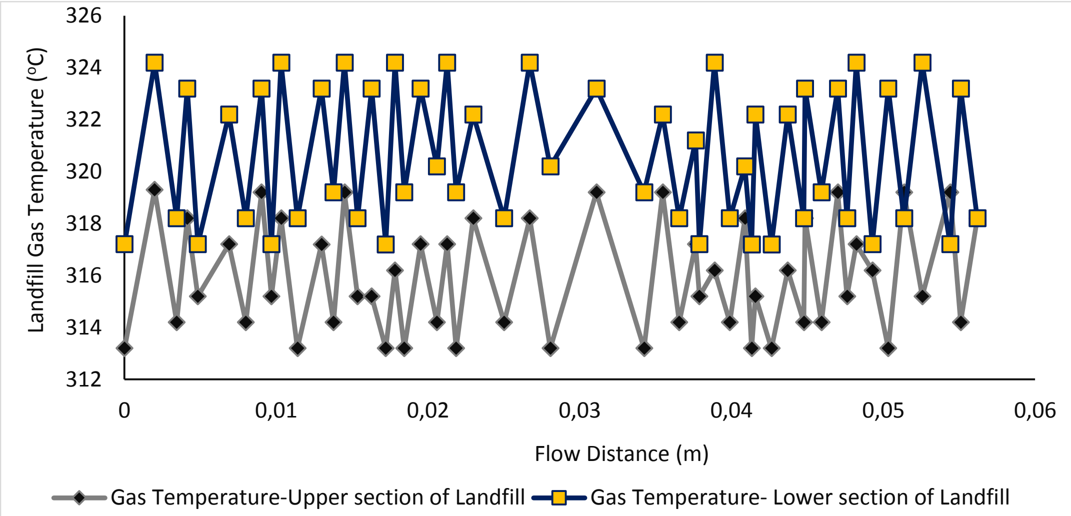

Figure 7f. *Landfill gas temperature variation at landfill temperature of 321 K*

Values obtained from the landfill model as the heat generation rate ranged from 0.111-2.837 W/m3 at mesophilic temperature range of 291-321, and correlated with landfill heat generation values reported in other investigations. Findings obtained from this study revealed that landfill gas temperature as well as the heat rate is maximum within the compacted waste stream placed in the landfill cells, and gradually reduces through cooling as it flows upwards from a region of higher concentration (around the decomposing waste stream at the lower section of the landfill) to a region of lower concentration (towards the gas holder at the upper section of the landfill). The study also indicated that constant increase in the landfill temperature can accelerate the rate of organic waste decomposition which in turn accelerates the gas generation and flow rate within the landfill. Finally, it is important to note that the biothermal process in a landfill system is optimum only when the pH of the feedstock is within the neutral range, internal temperature of the system is adequate to enhance decomposition, moisture content is sufficient to enable microorganisms thrive and above all, feedstock with proper carbon to nitrogen ratio is selected.

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