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Modeling of Heat Transfers in Bioreactive Household Waste Storage Facilities: Spatial and Temporal Distributions

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Abstract

In order to enhance the production of biogas and to study the thermal behavior of waste, a numerical study of fluid flows and heat transfers within household waste was developed to predict the distributions of thermal fields. The mathematical model is based on the conservation of mass and energy equations. The resulting system of equations is discretized using the finite volume method and solved using the Thomas algorithm. The results of the model studied are compared with the numerical and site measurements results from other authors. The results have been found to be in good agreement. The results show that the mathematical model is able to reproduce the thermal behavior in anaerobic phase in landfills. The isotherms revealed that temperatures are lower in the upper part of the waste cell, very high in the core and decrease slightly in the bottom of the cell due to the biodegradation of waste.

Keywords

Household Waste, Biogas, Temperature, Heat and Mass Transfer, Mathematical Model

1. Introduction

Currently, the world is facing many environmental problems related to waste management, climate change and global warming. In large African cities, demographic, economic and urban growth are often at the origin of a large production of waste. In Togo, since independence (1960), the population has continued to grow, resulting in a high production of waste. This increase in waste has led to a proliferation of household waste storage sites throughout the country, the sustainable management of which is a major challenge.

The most common means of disposing solid waste is landfilling. Solid waste that is dumped is rarely inert. Numerous physico-chemical and biological reactions take place not only between the waste and the receiving environment (soil, geological substratum, groundwater, etc.), but also within the waste itself [1]. For solid waste elimination, it is essential to study the parameters influencing their biodegradation.

Most factors controlling waste degradation and biogas production have been the subject of intensive research works. The parameters such as moisture content, temperature, pH, etc., which influence gas production in soil and sewage sludge digesters are investigated in [2]. It is found that there are the optimum temperatures (30˚C to 35˚C), pH and alkalinity which maximize gas production rates. This study reveals also that refuse composition affects the type and the quantity of gas produced. Environmental factors influence methanogenesis from refuse in landfill samples. The increasing moisture accelerated methanogenesis in 67% of the samples, but the rates decreased or remained unchanged in other samples [3]. Heat of reaction, specific heat of water/refuse mixtures, heats of neutralization, heat losses to air and soil, solar radiation and aerobic metabolism control the thermal regime of an anaerobic domestic refuse landfill. It is shown that even in temperate climates, landfill temperatures can rise to 45˚C and above under anaerobic conditions with the reduction in fatty acid concentrations in leachate [4]. Effects of moisture movement on methane production in solid waste landfill samples are studied [5]. The results show that moisture movement through a decomposing solid waste sample appears to increase methane gas generation rates by 25% to 50% over methane gas rates observed during minimal moisture movement but at the same overall moisture content levels. This study points out that moisture content and moisture movement are two separate variables affecting methane generation rates. Leachate recirculation and pH adjustment can prevent the inhibition of the anaerobic digestion of municipal solid waste by stimulating the waste degradation and methane production [6].

In order to study and compare different methods of landfill operation, a numerical model of hydro-thermal-biological coupling is ultimately a good way of predicting total production and the rate of methane production [7]. A model that integrates four distinct phases: two mobile phases (the gas and liquid phases) and two immobile phases (the solid and biofilm phases), is aborted [8]. Four classes of solid waste are considered, as well as five chemical species that are mainly present in gaseous or liquid form (N_2, CO_2, CH_4, O_2 and H_2O). The transport of each of these species is taken into account and a kinetic model of aerobic and anaerobic biodegradation is developed. In [9], is developed a one-dimensional multi-phase numerical model to simulate vertical settlement involving liquid and gas flows in a deformable settlement municipal solid waste landfill. The gas generation rate follows an exponential time decay function. The gas generation model developed on the basis of a first-order kinetic approach for a single bioreactor includes the governing equations for gas migration, liquid flow and landfill deformation [9]. Regarding thermal fields, the majority of temperature data found in the literature result from the modeling of heat transfer in landfills with little or no actual field temperature measurements [10] [11]. Some of these data have been direct reports of temperature trends over time in individual landfills with limited number of sites measurements and infrequent measurements [12] [13]. It is studied long-term spatial and temporal variations of temperatures, which have been investigated in covers, wastes, and liners at four municipal solid waste landfills located in different climatic regions: Alaska, British Columbia, Michigan, and New Mexico [14]. Temperatures are measured in wastes with a broad range of ages from newly placed to old (up to 40 years). The characteristic shape of waste temperature versus depth relationships consisted of a convex temperature profile with maximum temperatures observed at central locations within the middle third fraction of the depth of the waste mass. Lower temperatures were observed above and below this central zone, with seasonal fluctuations occurring near the surface and steady and elevated values (above mean annual earth temperature) near the base of the landfills. Overall, thermal regime of landfills is controlled by climatic and operational conditions [14]. The numerical modeling approach for predicting temperatures in municipal solid waste landfills is developed [15]. Model formulation and details of boundary conditions are described and model performance was evaluated using field data from a landfill in Michigan, USA. The numerical approach was based on finite element analysis incorporating transient conductive heat transfer. The results are presented and compared to field data for the temperature-dependent growth-decay functions. The formulations developed can be used for prediction of temperatures within various components of landfill systems (liner, waste mass, cover, and surrounding subgrade), determination of frost depths, and determination of heat gain due to decomposition of wastes. For their, numerical modeling of temperatures in landfills requires transient, nonlinear analysis to account for complex boundary conditions and temporal trends. In short, variability in heat generation functions resulted in different simulated temperature profiles for newly placed wastes and relatively older wastes. The overall variability of temperatures was greater at newer wastes than at older wastes. Maximum simulated temperatures at central depths reached approximately 42˚C for newly placed wastes and approximately 56˚C for older wastes. The model temperatures were within ±2˚C to ±5˚C of the measured temperatures. Thermal response including damping of seasonal temperature variations with depth, phase lag with depth, and onset and presence of heat gain due to waste decomposition were captured by the model. It is analyzed in [12] the temperature evolution of the Tokyo Port landfill, concluded that both aerobic and anaerobic activity affected the temperature of refuse, and that the temperature rise was mainly caused by anaerobic decomposition.

The characterization and analysis of the field temperature in a landfill situated in the south of France are done [16]. The spatial and temporal temperature variations were been recorded in municipal solid waste during the filling of the 200,000 m^3 landfill cell. The temperature increased rapidly within 20 days and the average temperature increase was about 20˚C. The thermal balance shows that the typical temperature increase mainly results from the heat produced by the consumption of the oxygen diffusing from the surface. Thus, the aerobic reactions are the main controlling factor for the initial temperature increase of a landfill. This stops when the refuse is covered either with other refuse or with a clay layer. In anaerobic conditions, the temperature becomes fairly uniform. At the end of the filling, the cell shows an isotropic temperature field around 50˚C to 60˚C, with high temperature gradients near the walls in contact with the air or soil.

The purpose of this work is to enhance biogas production though numerical study of fluid flows and heat transfers within household waste. The governing equations and the associated boundary and initial conditions are presented. The set of the equations is discretized using finite volume method. Thomas's algorithm is used to solve the algebraic equations obtained and the results after validation are presented in terms of temperature fields and profiles versus the depth of landfill cell and time.

2. Physical Problem and Mathematical Model

2.1. Physical Problem

The domain under study is a landfill cell of 40 meters deep and 40 meters large (**Figure 1**). At the right and left vertical boundaries, the cell is in contact with older waste. At the bottom boundary, the sealing is ensured by a geo-membrane. Due to the symmetry of the geometry of the cell, we restricted the study domain

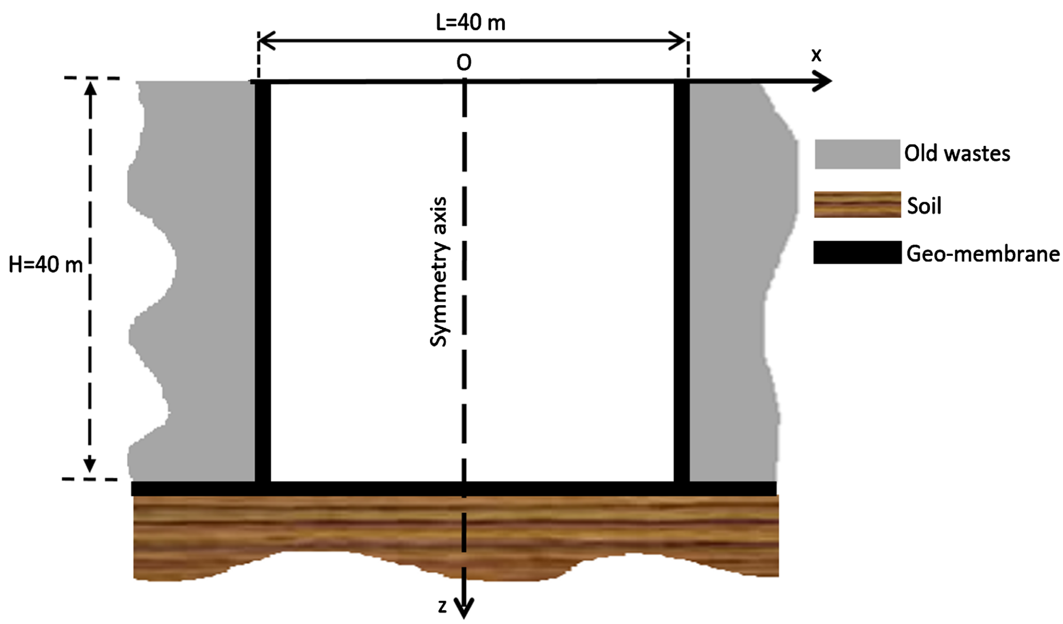

Figure 1. Schematic diagram of the landfilling of waste cells.

to a half landfill cell.

2.2. Mathematical Model

2.2.1. Main Assumptions

The assumptions made to establish the mathematical model are as follows:

- the landfills is considered as porous medium;
- the porous medium is undeformable; the porous solid matrix remains immobile despite of the degradation, settlement and humidification; energy transfer by radiation are neglected;
- the porous medium is considered homogeneous;
- there is thermal equilibrium between the different phases (solid, liquid and gaseous); the gas mixture is considered to be a perfect gas mixture;
- the terms of viscous dissipation and the effects of inertia are neglected (low fluid velocity); as a result, thermal convection is also neglected;
- the gaseous and liquid phases are considered immiscible and Darcy's law is applicable for both fluid phases; the convective velocity in the landfill porous layers is quite low, and the Reynolds number at this velocity does not exceed unity [17]; its value can be determined from the Darcy law;
- biogas is considered as an equimolar mixture of methane (CH_4) and carbon dioxide (CO_2).

2.2.2. Mass Conservation and Energy Equations

Hydrodynamic model is based on the conservation equation of mass and energy equation.

1) Mass conservation

The mass conservation equation for each phase is writing:

- liquid phase

$$\frac{\partial(m_l)}{\partial t}+\nabla(\rho_l \boldsymbol{U}_l)=-\dot{m}-\alpha_l \tag{1}$$

- gas phase

$$\frac{\partial(m_g)}{\partial t}+\nabla(\rho_g \boldsymbol{U}_g)=\dot{m}+\alpha_b \tag{2}$$

- vapor phase

$$\frac{\partial(m_V)}{\partial t}+\nabla(\rho_V \boldsymbol{U}_g+\boldsymbol{J}_V)=\dot{m} \tag{3}$$

- biogas phase

$$\frac{\partial(m_b)}{\partial t}+\nabla(\rho_b \boldsymbol{U}_g+\boldsymbol{J}_b)=\alpha_b \tag{4}$$

where m_j ($j = l$ for liquid, g for gas, V for vapor, b for biogas) is the mass of phase j, $\boldsymbol{U}_j\left(j=l,g\right)$ Darcy's velocity of phase j, $\dot{m}$ evaporation rate, $\boldsymbol{J}_j$ (j = V for vapor, b for biogas) diffusion mass flux density of phase j, α_l et α_b are respectively the moisture sink and the biogas production source term.

The Darcy law can be expressed as followed:

$$\boldsymbol{U}_j = -\frac{k_i k_{rj}}{\mu_j}\left[\nabla P_j - \rho_j \boldsymbol{g}\right] \tag{5}$$

where k_i is intrinsec permeability, k_{rj} is relative permeability of phase j, μ_j is dynamic viscosity of phase j, P_j and ρ_j denote pressure and density of the phase j, $\boldsymbol{g}$ is gravity acceleration.

2) Energy conservation

The energy equation can be written as followed:

$$\frac{\partial\left(\sum_i \rho_i h_i\right)}{\partial t} + \nabla\left(\sum_i \rho_i h_i \boldsymbol{U}_i\right) = \nabla\left(\lambda^* \nabla T\right) + \alpha_q \tag{6}$$

where h_i ($i = s$ for solid, l for liquid, g for gas) is the enthalpy of phase i per mass unit, λ^* the thermal effective conductivity, T the temperature and α_q heat source terms.

Using Darcy's law, others laws and the combination of the different equations with the main assumptions, the final model can summarize in three fundamentals equations. The three fundamentals equations have three main independent variables ω, T, P are respectively the water content, the temperature and the total pressure of the gas phase. Thus, we end up with a coupled system of three nonlinear differential equations. The thermal coefficients and the source terms are determined either experimentally, either mathematical or empirical models.

2.2.3. Production of Biogas

Waste biodegradation provides the source of gas production in landfills and biodegradation products are the main constituents of landfill gas. Waste nature and stage decomposition determine the landfill gas composition at any time. The landfill gas generation rate follows an exponentially decaying function of time. The gas generation model developed is based on a first-order kinetic single-bioreactor. So biogas production is defined by the exponential law which is principally defined for the anaerobic phase of degradation [18]:

$$\alpha_b = \sum_{i=1}^{3} f(\omega) A_i C_b \lambda_i(T) \exp\left(-\lambda_i(T) t\right) \tag{7}$$

where C_b is the potential biogas production, A_i is the fraction of each component (i = 1: rapidly biodegradable, i = 2: moderately biodegradable and i = 3: slowly biodegradable) and α_b is the rate of biogas production.

The degradation kinetics for each component A_i is defined by Arrhenius law:

$$\lambda_i(T) = \beta_i \exp\left(-\frac{E_{ai}}{RT}\right) \tag{8}$$

where β_i is a constant (hydrolysis rate of substrate i) and E_{ai} is the activation energy of each component. $f(\omega)$ is an empirical function of water content. The water content function used is based on the Gil Diaz (1995) model [19].

The heat production rate is obtained from hydrolysis and methane production rates by this relation:

$$\alpha_q = \frac{H}{2M_b}\alpha_b \tag{9}$$

where H is the energy released for each mole of methane which is produced during degradation and M_b is the molar mass of biogas.

For the energy released, it can be found several values in the literature [7], [19] [20] [21] [22] [23]. It is proposed the values of energy between 2 and 60 kJ per mol [20]. A value used in our model for heat production is 50 kJ·mol^{-1}.

The moisture sink during the anaerobic phase is obtained by the following formulation [20]:

$$\alpha_l = \frac{1}{2\times 1.7}\frac{M_{H_2O}}{M_b}\alpha_b \tag{10}$$

M_{H_2O} is the molar mass of water vapor.

2.2.4. Boundary and Initial Conditions

The boundary conditions are defined as follow: -at the top horizontal boundary, a zero-flux condition is used for humidity (ω), the pressure (P) condition is equal to the atmospheric pressure and for the temperature (T), convective exchange is considered;

- a zero-flux condition on the vertical boundary and on symmetric axis;
- and a zero-flux condition except the temperature condition which is equal to the ground temperature on the bottom horizontal boundary.

The initial water content, pressure and temperature in the landfill are estimated respectively 54%; atmospheric pressure and average ambient temperature equal to 298.15 K.

2.2.5. Model Parameters

The thermal and biological parameters of the waste [7] [9] [18]-[23] used in the present work are presented in **Table 1**.

Different values of porosity, hydraulic conductivity of Municipal Solid Wastes (MSW) and water content are proposed in the literature. The choice of values of porosity and hydraulic conductivity is based on the values proposed by different authors and on their estimation from site data and resistivity charts [19]-[30]. The hydraulic parameters used are: a porosity of 65%, a hydraulic conductivity equal to $2.5\times10^{-4}\,e^{-0.103z}$ (m·s^{-1}) where z is the depth of the landfill cell and a residual water content equal to 25%. For Van Genuchten parameters,

$$m = 1 - \frac{1}{n} = 0.8718 \quad \text{and} \quad \alpha = -10 .$$

Thermal conductivity of the landfill is an important parameter. For a simulation, it is considered an average thermal conductivity proposed by [20] [23] and [31]. In the present work, it is used a value of 0.09 Wm^{-1}·K^{-1}.

3. Numerical Method and Validation

3.1. Numerical Method

The finite volume method is used to solve the equations system. It consists of

Table 1. Biological and thermal parameters for simulation model.

Parameters	Values
Hydrolysis rate of substrate (s^{-1})	
β_1	5.815×10^{-5}
β_2	1.454×10^{-5}
β_3	2.907×10^{-6}
Activation energy (K)	
E_{ai}/R	1561.10
Reaction rate constant of refuse (s^{-1})	
λ_1	4.63×10^{-7}
λ_2	1.157×10^{-7}
λ_3	2.315×10^{-8}
Gas (biogas) generation potential per unit mass of refuse (m^3/kg waste)	
C_b	0.12
Refuse composition or component (%)	
Rapidly biodegradable A_1	15
Moderately biodegradable A_2	55
Slowly biodegradable A_3	30
Heat source term ($kJ\cdot mol^{-1}$)	
H	50

integrating nonlinear partial differential equations on elementary volumes that surround each node. The advantage of this method is the local flux conservation, the respect of the maximum principle, the possibility to apply it on any mesh (structured or unstructured meshes). It is particularly suited to the equations of fluid mechanics, heat and mass transfer, reservoir simulation in petroleum engineering. This method, is classically used in the oil reservoir simulation setting [32], appears to be very stable and efficient for solving conservation equations of mass and energy (conservation of mass, momentum and energy). The temporal discretization is based on a Cranck-Nicholson method. For a time step Δt, knowing the value of the variable at the time $n\Delta t$, it is necessary to determine its new value at the time $(n+1)\Delta t$ where n is the iteration number. The resulting algebraic equations are solved using the Thomas algorithm.

3.2. Validation of the Numerical Model

The present numerical code is validated by applying it to a rectangular physical domain with 40 meters depth and 20 m wide representing half landfill waste cell. The vertical boundaries of the landfill cell are in contact with an older waste cell. The bottom and the vertical boundaries of the landfill waste cell are completely sealed by the geo-membrane. A comparison between the results of the present work and those of [20] (**Figure 2**) show an acceptable agreement qualitatively

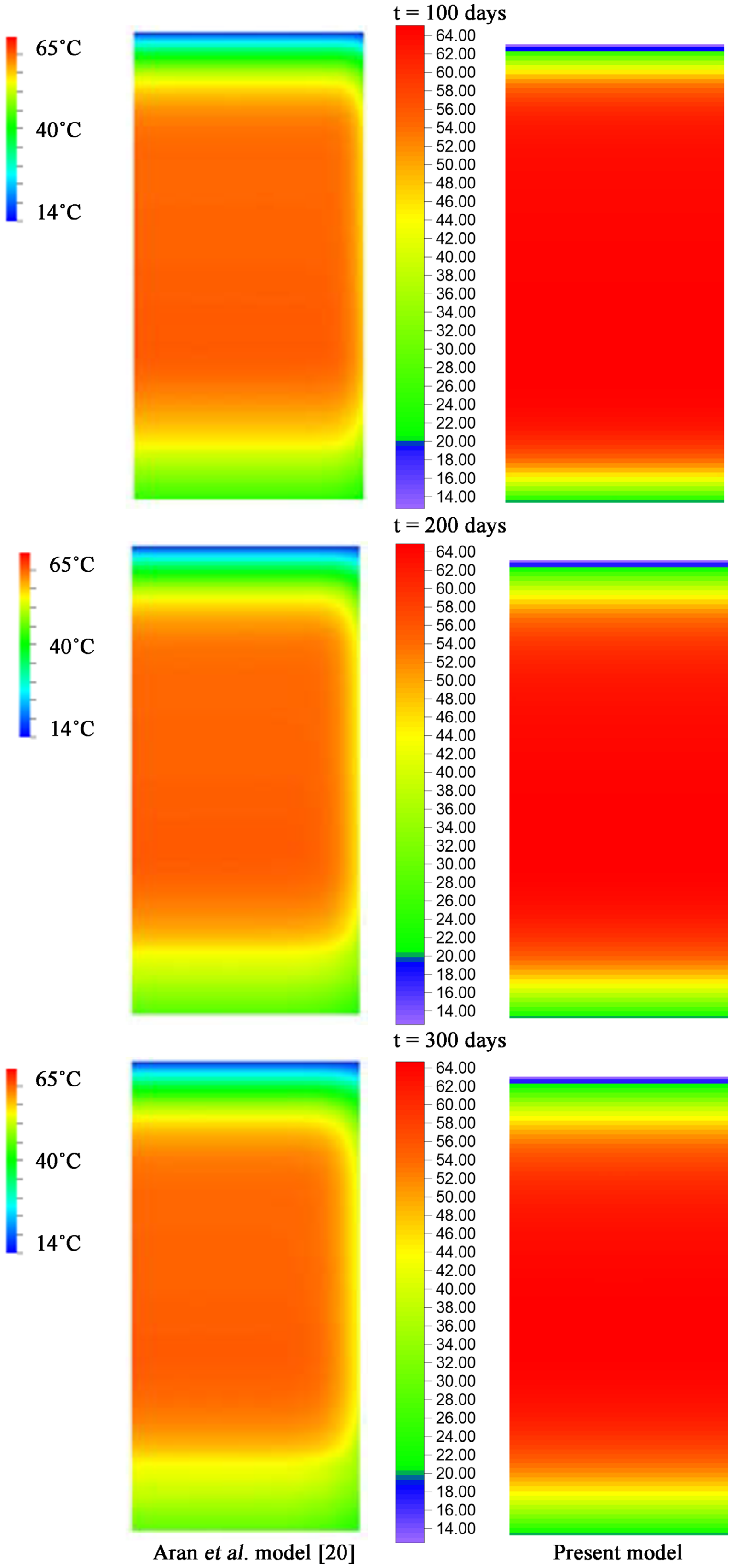

Figure 2. Comparison of the distribution of thermal fields in landfill waste cell.

and quantitatively.

According to the results in [20], the temperature fields are characterized by relatively warm cores with temperatures around 65˚C and lower temperatures at the top and bottom side of landfill wastes cell. The present work results corroborate with those of [20]. But it can be noticed a slight difference between the distribution of the temperature fields of the two models. The upper and the bottom zone with low values of temperature are larger for [20] model than those of the present study. This slight difference can be explained by the difference between the values of some parameters used in the simulation and by the fact that the nature of waste used in [20] is not known as well as the initial temperature of wastes.

4. Results and Discussion

In this part, the results found in the present numerical simulation has been discussed. The temperature of the landfill is set to 25˚C and the simulation is performed using climate data of Togo (**Table 2**) from 2021.

Figure 3 shows the stratification of the temperature of the landfill as the case previously studied. It can be observed that the distribution of the landfill temperature depend weakly on the climate data. The temperature increases from the surface of the landfill cell towards the center and then decreases from the center to the bottom.

Thus the lower temperature is found at the vicinity of the surface and the bottom of the landfill cell when the core of the landfill is characterized by high value of temperature. These results can be explained by the fact that the temperature of the upper zone of the landfill layers depends on seasonal variations of

Table 2. Climate data of Togo (National metrological Service of National Aviation Security Agency (*ASECNA*)).

Months	Temperature (˚C)	Solar Flux Density ($W \cdot m^{-2}$)
January	28.5	591.9
February	29.7	714.3
March	29.9	750.02
April	28.7	800.4
May	27.8	705.0
June	26.5	570.8
July	25.4	691.2
August	24.5	584.8
September	25.3	758.6
October	27.1	776.5
November	28.0	690.5
December	28.3	617.0

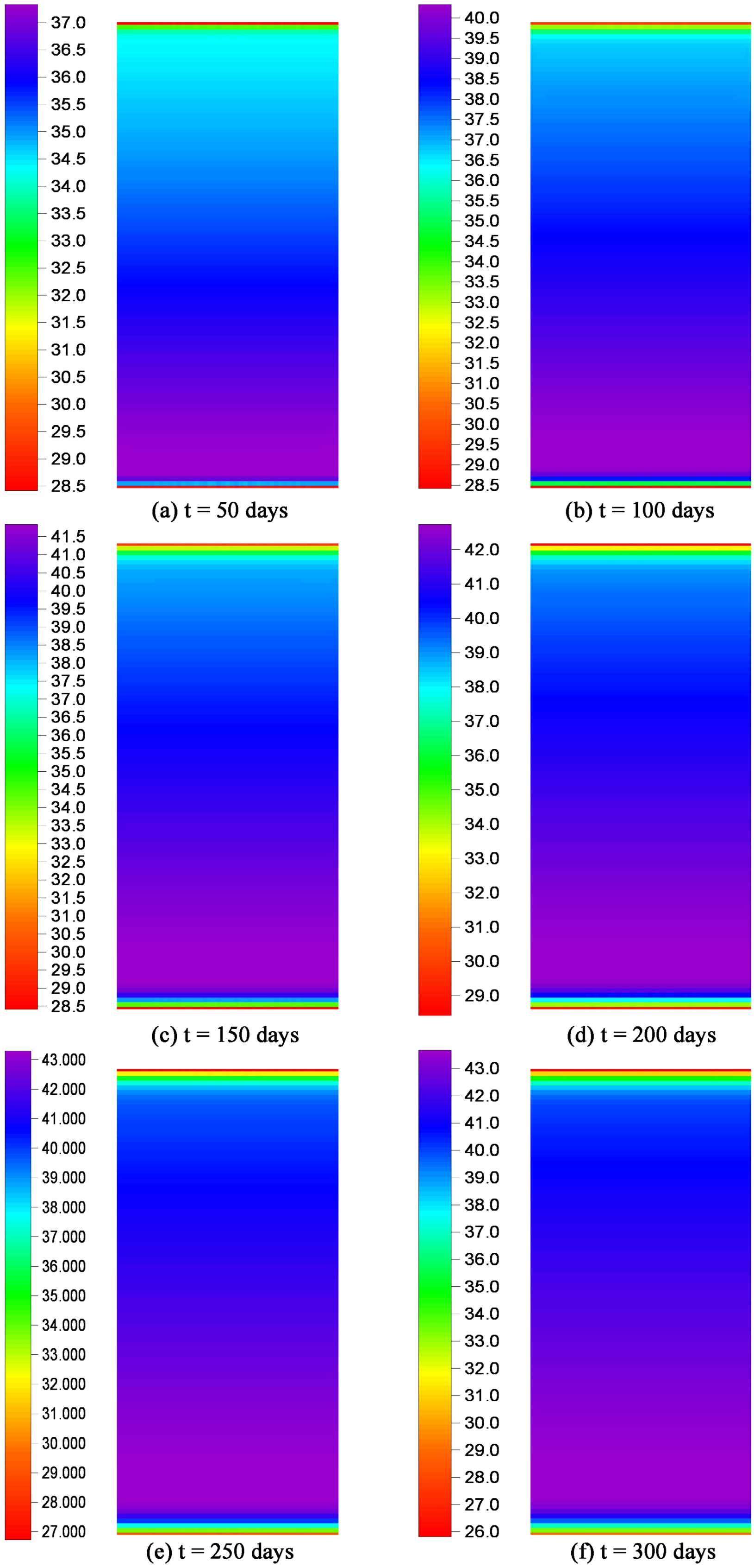

Figure 3. Evolution of temperature distribution in the landfill.

ambient air temperature when the temperature of the bottom of the landfill cell is affected by the ground temperature that results in the ambient temperature applied at the surface of the ground. The core of the landfill cell is the main biodegradation zone. This biological reactions release heat inside the waste increasing then the temperature in the core of the landfill. These results corroborate with the sites measurements of [19] which shows that the temperature near the landfill cell surface varies from 15˚C to 20˚C depending on the seasonal variations and that of the bottom part varies from 35˚C to 60˚C and sometimes more in the deeper layers. The temperature decreases at the bottom of the landfill and always remains higher than the ground temperature. This observation is, in general, true for all the simulations of heat transfer throughout the landfill.

The analysis of the temperature distribution within the landfill (**Figures 3(a)-(f)**) shows also that the isotherms do not change significantly over time due to the low thermal conductivity of the waste, which behaves as an insulator. Thus, heat transfers of waste with the surrounding environment are not very important and the heat losses have been compensated by the low heat production of the anaerobic phase biodegration of waste.

Figure 4 presents the variation of temperature versus z-coordinate for different vertical sections of the landfill for 50 days and 300 days of simulation duration. The analysis of the temperature profile shows an increase in temperature from the surface to the core and followed by a decrease towards the bottom of the cell. The temperature is lower at the top of the cell but is slightly higher than the ambient temperature. There is also a low vertical thermal gradient between the layers in the core. For 50 days of simulation, the maximum temperature is 37˚C but it is 43˚C for 300 days of simulation. The maximum temperature of the waste increases in time due to biological activities. These results are in good agreement with the literature data. According to [15] et [33], the temperature increases up to 55˚C in the core and there is a thermal gradient of 1˚C/m - 10˚C/m

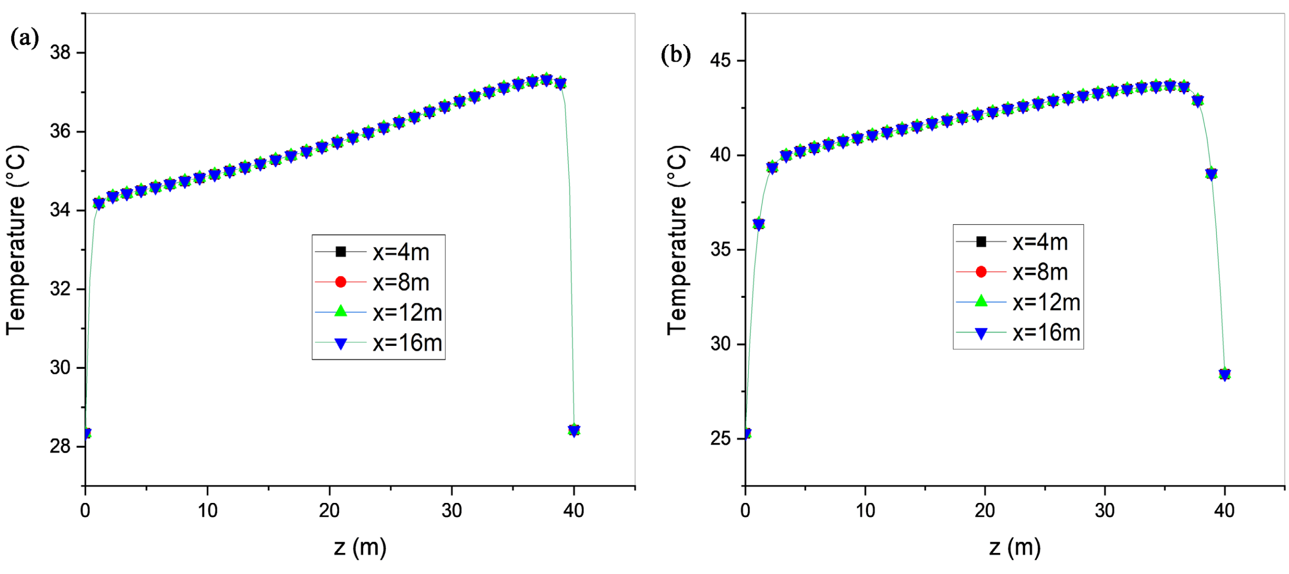

Figure 4. Waste temperature profile as a function of the height. (a) t = 50 days; (b) t = 300 days.

between the different layers. The thermal gradient is larger in the surface layers and decreases with depth [16] and [17]. The upper layers are more influenced by the outdoor temperature [33] and seasonal changes and there is a mismatch between the maximum temperature values of the waste and the outdoor temperature related to the thermal diffusivity of the waste and the clay layer. This shift is also observed on site and reported by some authors [33].

In general, the thermal profiles are characterized by relatively warm cell cores and lower wall temperatures related to the external temperature and the soil temperature at the bottom of the cell. It is also noted by [20] that the thermal profiles are characterized by relatively warm cores (temperatures around 65˚C or more) and lower wall temperatures related to the outside temperature and the soil temperature at the bottom of the locker. He states that these profiles strongly resemble those observed at other sites or obtained by numerical or experimental simulations by [12] [31], which would seem to indicate that each landfill is not a unique case.

Moreover, their appearance corresponds to that observed at the end of the filling of a domestic waste landfill. This means that the exploitation phase is essential in the establishment of the thermal fields in landfill [23]. The study conducted in [33] examined the thermal aspects of municipal waste landfills as a function of operational conditions and climatic region. Spatial and temporal distributions of waste temperatures were determined in four landfills located in North America (Michigan, New Mexico, Alaska and British Columbia) over monitoring periods ranging from 9 months to over five (5) years. Waste temperatures at shallow depths (6 to 8 m) and near the edges of cells within about 20 m conformed to seasonal variations, while constant high temperatures of 23 to 57˚C is reached at deep and central locations. Temperatures decrease from high levels near the base of the dumps, but remain above ground temperatures [33].

The analysis of the profiles of waste temperature (**Figure 4**) shows that the profiles of the temperature remain the same in different vertical section of the landfill due to the horizontal stratification of the temperature distribution. The temperature varies weakly in the vertical section but strongly in horizontal section of the landfill. This can be explained by leachate gravity flow towards the bottom of the waste, which affects the distribution of the temperature and pressure in the waste.

Figure 5 depicts the evolution over the time of the waste cell temperature. For all the profiles, it can be noticed an increase in temperature with time. The stabilization of temperature is observed around one year. The increase in temperature with time is due to heat generation within the waste. Considering the different depths, it can be seen that the temperature becomes more and more important when progressing towards the core of the waste cell. Thus, the position ($x = 10$ m; $z = 8$ m) is at lower temperature values than the position ($x = 10$ m; $z = 12$ m). The temperature values observed at the position ($x = 10$ m; $z = 32$ m) is high because this position is located in the core of the waste box where the temperature is higher. It can be stated that at the vicinity of the ground, the temperature

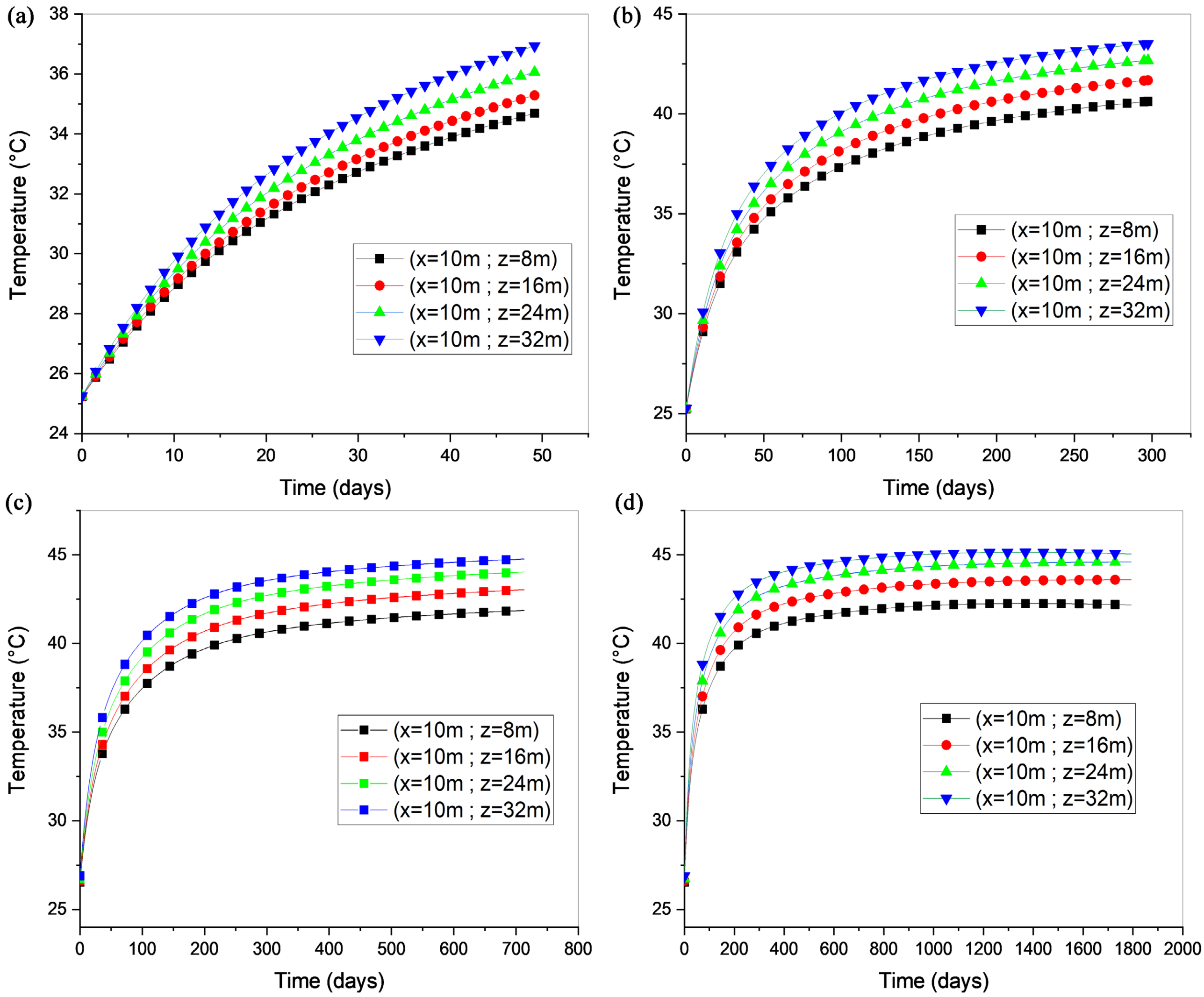

Figure 5. Temporal variation of waste temperature for $x = 10$ m at various depths. (a) t = 50 days; (b) t = 300 days; (c) t = 730 days; (d) t = 1825 days.

values decrease and remain slightly higher than the ground temperature.

The evolution of the temperature versus time is studied by other authors. The temperature changes as a function of time at two bioreactor sites in France using temperature sensors is studied in [19]. It is observed that waste temperatures vary from 15˚C to 20˚C depending on seasonal variations in the surface layers and 35˚C to 40˚C in the deeper layers at both sites. The range of temperature changes can be as high as 16˚C to 30˚C depending on the depth. The surface layers are more influenced by changes in the outside temperature. The difference in thermal behavior at the same depths but at different points in the same site can be explained by the heterogeneity of the waste. This heterogeneity can be related to the variability of the physical composition of the waste and therefore of the values of hydraulic and thermal conductivity and heat capacity. These parameters are very different depending on the materials (metals, wood, paper, glass, etc.). Temperature heterogeneity can also be linked to the heterogeneity of the water content and the state of degradation of the waste. A vertical temperature gradient of 2˚C/m - 10˚C/m is also generally observed in the center of the facility. The temperature of the waste can reach 55˚C - 60˚C and stabilize after one year [34] [35]. In our model, the temperature stabilization time is a little over one year. The temperature stabilization time is not the same for all wastes but a value of one year seems to be a general order of magnitude [36]. A numerical modeling approach for predicting temperatures in municipal solid waste landfills is conducted by [35]. The simulated and measured temperatures were higher at older wastes cell (B) than at newly placed wastes cell (D). Maximum simulated temperatures at central depths reached approximately 42˚C for cell D and approximately 56˚C for cell D.

In general, regarding the literature, for total waste height between 20 to 60 m in the studies that were conducted over time, the maximum measured waste temperatures reported in literature varied from approximately 40˚C to 65˚C.

Relatively similar trends were observed in studies with one-time sampling events [14] [37] [38]. In [39], it can be noticed that cover temperature variations typically follow seasonal trends with amplitude decrement and phase lag with depth. Long-term temperatures between approximately 30˚C and over 50˚C were observed for bottom liner systems and bases of landfills [39]. Liner temperatures were elevated (with respect to local air and ground temperatures), however lower than the maximum waste temperatures [12] [13] [40].

5. Conclusions

Numerical study of two-dimensional (2D) mathematical model based on conservation equations of mass, energy and pressure using a finite volume method to model waste landfill was carried out in the present paper. The coupled hydro-thermo-biological model is based on the Monod's classic model (1949) which biogas production is obtained directly from the degradation of solid waste according to a first-order degradation kinetics of the biodegradable fractions of the waste. The coupled model also contains a two-phase flow model based on Darcy's law.

The results of numerical simulations show that the temperatures of the waste around the surface of the cells (at shallow depth) are low and are related to the outside temperature or to seasonal variations. High temperatures are reached at depth and at central locations. These temperatures decrease from the elevated levels near the base of the landfills (at the bottom) but remain above ground temperatures. The heat generations within the waste, heat capacity of waste, the thermal conductivity, the initial values of biological parameters and the decay rate and as well as gas production rate are the parameters which influenced the thermo-biological behavior of landfill. The results are quite acceptable in terms of the temperature evolution and illustrate the advantages of such models for waste management.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

L	:	Depth	[m]
H	:	Width	[m]
m_j	:	Mass of phase j	[kg]
U_j	:	Darcy's velocity of phase j	$[m \cdot s^{-1}]$
ρ_j	:	Density of phase j	$[kg \cdot m^{-3}]$
$\dot{m}$	:	Evaporation rate (mass rate of water transfer from phase l to phase v)	$[kg \cdot m^{-3} \cdot s^{-1}]$
α_l	:	Moisture sink source term	$[kg \cdot m^{-3} \cdot s^{-1}]$
α_b	:	Biogas production source term	$[kg \cdot m^{-3} \cdot s^{-1}]$
α_q	:	Heat source term	$[J \cdot m^{-3} \cdot s^{-1}]$
t	:	Time	[day]
$\boldsymbol{J}_j$	:	Diffusion mass flux density of phase j	$[kg \cdot m^{-2} \cdot s^{-1}]$
k_i	:	Intrinsec permeability (absolute permeability)	$[m^2]$
k_{rj}	:	Relative permeability of phase j	
P_j	:	Pressure of the phase j	[Pa]
$\boldsymbol{g}$	:	Gravity acceleration	$[m \cdot s^{-2}]$
μ_j	:	Dynamic viscosity of phase j	$[N \cdot s \cdot m^{-2}]$ or $[Pa \cdot s]$
h_j	:	Enthalpy of phase j	$[J \cdot kg^{-1}]$
T	:	Temperature	[K]
P	:	Pressure	[Pa]
C_b	:	Potential biogas production	$[kg \cdot m^{-3}]$
A_i	:	Fraction of each component i ($i = 1$: rapidly biodegradable, $i = 2$: moderately biodegradable and $i = 3$: slowly biodegradable)	[%]
E_{ai}	:	Activation energy of each component i ($i = 1$: rapidly biodegradable, $i = 2$: moderately biodegradable and $i = 3$: slowly biodegradable)	[J]
R	:	Ideal gas constant	$[J \cdot mol^{-1} \cdot K^{-1}]$
H	:	Energy released for each mole of methane	$[kJ \cdot mol^{-1}]$
M_b	:	Molar mass of biogas	$[kg \cdot mol^{-1}]$
M_{H_2O}	:	Molar mass of water vapor	$[kg \cdot mol^{-1}]$
E_{ai}/R	:	Activation energy	[K]
		Greek symbols	
λ^*	:	Thermal effective conductivity	$[W \cdot m^{-1} \cdot K^{-1}]$
ω	:	Water content (wet mass of waste/dry mass of waste)	

Continued

λ_i	:	Reaction rate constant of refuse i	[s^{-1}]
β_i	:	Hydrolysis rate of substrate i (by Arrhenius law)	[s^{-1}]
		Subscripts and superscripts	
l	:	Liquid	
g	:	Gas	
V	:	Vapor	
b	:	Biogas	
s	:	Solid	
*	:	Porous medium	