Heat Flux Predictions for a 3-D Compost Model

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Abstract: A 3-D compost model was constructed based on a truncated cone geometry (4 m radius and 3 m height); in this, an energy balance is applied for a two phase system (solid-air). Compost energy processes are modeled with a modified heat transfer equation which includes: volumetric heat capacity, chemical oxidation and biological growing and inhibition. A sensitivity parameter analysis was run in order to get temperature predictions closer to the ones observed in organic residues composting processes; in which, according to reports, it is required 40-90 days in order to get temperatures in the range of 313 -343 K. Obtained predictions have shown that the composting process exhibits higher sensitivity to parameters as: compost material oxidation activation energy, biomass growth activation energy. Otherwise, middle sensitivity is exhibited respect to parameters as: biomass growth oxidation factor, porosity, compost thermal conductivity, biological heat generation and biomass density.

Keywords: compost, heat generation, parameter sensivity

1. Introduction

Biodegradation compost systems are an alternative for treatment of organic solid wastes, since this process allows an organic matter volume reduction of materials to be disposed, and at the same time provides an useful product for soil improvement [1,2]. Composition, color and texture of the composted material are function of both used residues and applied technique [1].

Industrial compost piles have been matter of study and mathematical modeling, some of these models have focused on the auto ignition phenomena, in which heating is attributed to organic matter oxidation and biological activity; steady state temperature predictions from these models are in the range of 350-530 K, and required time for reaching the steady state time goes from 26 to 31 weeks [3, 4, 5, 6].

2. Governing equations

A compost pile is considered formed by solids and air, then, this system can be modeled like a two phase porous media. Compost pile heating has been approached setting up an energy balance based in Fourier heat transfer equation, which is modified by additional terms in order to account for: heat generation from organic matter oxidation, as well as the one from biological process [3, 4, 5, 6]; these contributions are calculated using an Arrhenius type kinetic equation [7,8]. Also, effective thermal properties are calculated for the two phase system considering compost material representing the solid fraction, while air contained in the inner porous of the solid phase corresponds to the void fraction or porosity of the media [9.10]:

$$(\rho C)_{ef}\frac{\partial T}{\partial t} = k_{ef}\nabla^2 T + (1-\varepsilon)Q_c\rho_c A_c\,exp\left[\frac{-E_c}{RT}\right] + (1-\varepsilon)Q_b\rho_b\frac{A_1 exp\left[\frac{-E_1}{RT}\right]}{1+A_2 exp\left[\frac{-E_2}{RT}\right]} \qquad (1)$$

With:

$$k_{ef} = \varepsilon k_a + (1-\varepsilon)k_c \qquad (2)$$

$$(\rho C)_{ef} = \varepsilon\rho_a C_a + (1-\varepsilon)\rho_c C_c \qquad (3)$$

Equation 1 is a modified Fourier heat transfer equation, in which the second term on the right side corresponds to heat contribution from organic matter oxidation, and the third one accounts for heat contribution from biological process, both expressions are formulated like an Arrhenius function, in which there is an explicit temperature dependence:

$$k = A_x\,exp\left[\frac{-E_x}{RT}\right] \qquad (4)$$

Values of the involved parameters are reported in Table 1

Table 1. Parameters used in equations 1-3

Parameter	Symbol	Value	Ref
Factor for oxidation of the cellulosic material	A_c	1.8×10^3 s^{-1}	3,4,6
Factor for the oxidation of the biomass growth	A_1	2×10^6 s^{-1}	3,4,6
Factor for the inhibition of biomass growth	A_2	6.86×10^{30} 6.86×10^{32}	3,4 6
Heat capacity of air	C_a	1005 J kg^{-1} K^{-1}	3,4,6
Heat capacity of cellulosic material	C_c	3320 J kg^{-1} K^{-1}	3,4,6
Activation energy form cellulosic material oxidation	E_c	1.1×10^5 J mol^{-1}	3,4,6
Activation energy for biomass growth	E_1	1×10^5 J(biomass $mol)^{-1}$	3,4,6
Activation energy for biomass growth inhibition	E_2	2×10^5 J(biomass $mol)^{-1}$	3,4,6
Exothermicicty for cellulosic material oxidation	Q_c	17×10^6 J kg^{-1}	3,4,6
Exothermicity for biomass oxidation per kg of dry cellulose	Q_b	6.6x106 J kg^{-1}	3,4,6
Ideal gas constant	R	8.314 $JK^{-1}mol^{-1}$	3,4,6
Temperature	T		
Effective thermal conductivity of air	k_a	0.026 W m^{-1} K^{-1}	3,4,6
Effective thermal conductivity of cellulose	k_c	0.3 W m^{-1} K^{-1} 0.18 W m^{-1} K^{-1}	3,4 6
Effective thermal conductivity of the bed	k_{eff}	W m^{-1} K^{-1}	3,4,6
Time	t	s	3,4,6
Porosity	ε	0.3	3,4,6
Effective thermal capacity per unit volume of compost	$(\rho C)_{eff}$	J m^{-3} K^{-1}	3,4,6
Air density	ρ_a	1.17 kg m^{-3}	3,4,6
Bulk biomass density	ρ_b	575 k m^{-3}	3,4,6
Cellulosic material density	ρ_c	1150 k m^{-3}	3,4,6

Sidhu et al [3] used a 2-D geometry for simulation of a compost pile with dimensions of 44m x 11m, as well as one of 80m x 20m; in another publication [4] they tried with variations in the ratio height/length like ¼, 1/8, for these systems predicted steady state temperatures are in the range of 350-380 K. A different geometry is reported by Moraga y Zambra [6], they used a 9.2m x6m x3 m rectangular prism, after 31 weeks predicted steady state temperature was 528.26 K.

Considering that in conventional compost systems an optimal thermophilic microorganisms growth is obtained when temperature is in the range 313-343 K [8]; and the required composting time is 40-90 days [1, 2]. Then, compost simulation is approached considering a truncated cone geometry, the energy balance described in equations 1-3; in order to get temperature and time predictions according to those observed in conventional compost systems, parameters were modified based on a sensitivity parameter analysis and reported experimental data.

3. Use of COMSOL Multiphysics

Process simulation was implemented in COMSOL Multyphisics 3.4 using the following route: Chemical Engineering/Energy Transfer/Convection and Conduction. The reference geometry is a truncated cone of radius=4m and height=3 m; temperature initial condition is the air temperature; and, boundary conditions considered a thermal insulation at the base, and air temperature for lateral and top exposed area.

The initial step was to introduce parameter values as reported by Sidhu et al [3, 4], by doing so a steady state temperature increment of 0.156 K was predicted.

For getting predictions according to the ideal ones observed in a composting system, it was necessary to run a parameter sensitivity analysis. Taking as basis published works using equations 1-3 [3, 4, 6], as well as those of experts [1, 2, 7, 8, 11] parameter modification was set up considering a variation between -50% to +25%.

4. Results

Results of the parameter sensitivity analysis allowed to classified them as follow:

a) Constant: C_a, k_a, ρ_a
b) Low impact: A_c, A_2, C_c, E_2, Q_c, ρ_c
c) Average impact: A_1, ε, k_c, Q_b, ρ_b
d) High Impact: E_c, E_1

The last group accounts for Arrhenius type heat generation terms of equation 1. According to Johnson [7] activation energy for biomass growth (E_1) should be between 42 and 84 KJ (biomass mol)$^{-1}$; while the inhibition energy of biomass growth (E_2) is between 250-330 KJ (biomass mol)$^{-1}$, thus $E_2>E_1$ since biomass activity inhibition is more sensitive to high temperatures than the one for biomass growth.

Replacement of E_1 (100 KJ(biomass mol)$^{-1}$) by Johnson [7] suggested minimal value (42 KJ(biomass mol)$^{-1}$) predicted a steady state temperature of to $1x10^9$ K; starting from the minimal value, E_1 was incremented in short steps, up to an intermediate value of 84 KJ(biomass mol)$^{-1}$, this allowed to obtain a steady state temperature prediction near to 400K.

Replacement of E_2 by Johnson reported value (250 KJ (biomass mol)$^{-1}$) did not show a significant impact on temperature predictions.

Solid phase properties (k_c, E_c, A_c, ρ_c, Q_c, C_c) were not modified since most of them agree with reported values for organic wastes used in domestic and agricultural compost production (domestic wastes, straw, leaves, yardwastes).

About porosity, it has been reported that an optimal composting process requires a porosity between 32 and 36% [12]; previous works [3, 4, 6] used a porosity of 30%, although any modification of this parameter will impact straightforward on the effective volumetric heat capacity ($(\rho C)_{eff}$) as well as the effective thermal conductivity (k_{eff}), a porosity value of 0.34 made the product $(1-\varepsilon)Q_b\rho_b$ decrease in 15% respect to other reports. Finally values for ρ_b and Q_b were adjusted in order to get the temperature predictions according to experimental field observations.

A resume of main modifications to parameters is presented in Table 2.

Running the model with the values reported in Table 2 a steady state temperature of 342.66 K was predicted. Once the model runs in steady state conditions, a transient simulation was done with time steps of 1day; temperature prediction for 20, 30, 50 and 60 days are shown in Figures 1, 2, 3, 4. As can be seen heat evolves from the center of the system to the boundaries.

Table 2. Resume of parameter modification

	Old value	Ref	New value	Ref	Modif
A_1	$2x10^6$ s^{-1}	3,4, 6	$1x10^6$ s^{-1}	---	-50%
ε	0.3	3,4, 6	0.34	12	+13%
E_1	$1x10^5$ J(biomass mol)$^{-1}$	3,4, 6	$8.4x10^4$ J(biomass mol)$^{-1}$	7	-16%
E_2	2x105 J(biomass mol)$^{-1}$	3,4, 6	$2.5x10^5$ J(biomass mol)$^{-1}$	7	+25%
ρ_b	575 kgm^{-3}	3,4, 6	546 kgm^{-3}	---	-5%
Q_b	$6.66x10^6$ Jkg^{-1}	3,4, 6	$6.327x10^6$ Jkg^{-1}	---	-5%

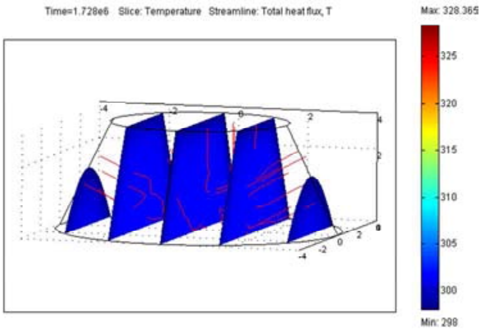

Figure 1. Temperature and heat flux predictions for a 20 days period of composting process

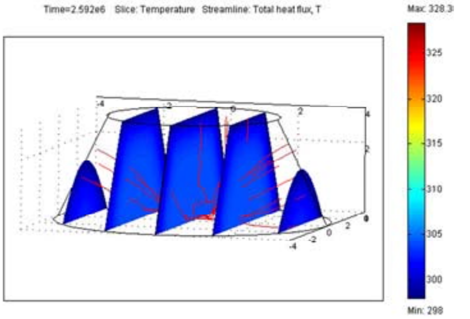

Figure 2 Temperature and heat flux predictions for a 30 days period of composting process

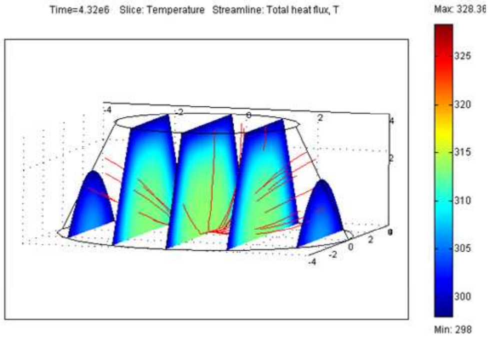

Figure 3. Temperature and heat flux predictions for a 50 days period of composting process

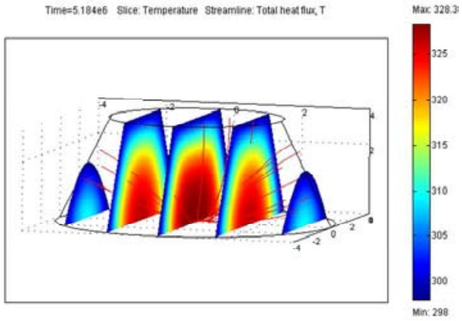

Figure 4. Temperature and heat flux predictions for a 60 days period of composting process

5. Conclusions

Modeling approach has produced satisfactory predictions, which are similar to those observed in conventional compost systems.

Although it must be recognized that in order to best reflect the real conditions in a composting system it should be desirable that model formulation take into account conditions like humidity, pH, volume change due to the collapse of degraded material; also, in high sunlight conditions, energy balance should include a radiation term for heat absorption

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