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*Research Article*

# Integrated Quantitative Analysis for Designing of Composting System

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**Abstract.** Composting is a solid waste treatment method that being widely applied in a larger scale treatment facility due to its advantage on energy consumption and low-level technologies aspects. However, composting that currently being applied to a large- scale treatment facility is lack of systematic approaching, which is resulted in adverse effects on quality of final product, time cost, energy cost and spatial cost. Moreover, because of dealing with flammable byproducts from microbiological decomposition reaction under moderately high-temperature, safety of the facilities must be ensured. This research proposes a new approach to analyze systematically the biological decomposition process in the compost pile. Heat generation by the reaction, as well as water movement and oxygen consumption phenomena shall also be captured by proposed coupled mass and energy balance equations for each of those substances. A biological model for microbial decomposition process is proposed mathematically regarding all primary factors affecting the microbial activities. The analysis system is finally applied to designing a better composting system having lower cost, lower energy consumption, environmental friendly and safer than ever.

**Keywords:** Composting, BioDuCOM, Mass and Energy Transport, Microbiological Model, Compost Analysis.

## Introduction

Composting is one of the biotechnological treatment methods for biodegradable solid waste. It is being widely applied in a larger scale treatment facility due to its advantage on the aspects of less energy consumption and low-level technologies. However, the composting system that is currently being applied, especially a large-scale treatment facility, is lack of systematic approaching. In large-scale treatment system, flow of substances and energy in compost pile tend to be more important than those of the smaller scale system. Lacking of precisely understanding of those phenomena leads to poor quality of the final product, more time, energy and spatial cost. Moreover, because the treatment processes deals with highly flammable byproducts, such as methane, from microbiological decomposition reaction under moderately high-temperature, it is indispensable to reduce the risk of accident and ensure safety of the facilities.

This paper proposes a new approach to simulate the biological decomposition processes in the compost pile in aiding in designing for the optimized large-scale composting system. Heat transport, moisture migration and oxygen diffusion phenomena shall also be captured by proposing the coupled mass and energy balance equations for each of those substances. A biological model for microbial decomposition process is proposed mathematically taking into account of all primary factors affecting the microbial activities. Those factors are substrate concentration, its physical and chemical properties, microbial concentration, temperature, dissolved oxygen concentration, and moisture content inside the compost. Basis of the analysis system has been designed to be widely applicable to all types of the biodegradable solid waste to maximize an application range of the analysis system.

The mass and energy balance equations and the biological activities governing model were integrated into a 3D FEM computer program based on the DuCOM technologies (Durability of Concrete Model, University of Tokyo), which is resulted in a total analysis program, namely BioDuCOM, that has ability to simulate the primary phenomena occurred inside the compost pile. With benefits of adopting the FEM, most of external treatment methods for controlling the compost condition can also be simulated. For example, heat supply or drying by air blower/heater, water supply by sprinkle, water drainage, etc. Consequently, systematical designing of more complicated composting system having lower cost, lower energy consumption, environmental friendly and safer, becomes possible.

## Theories of Analysis System

### *Overview*

During biological decomposition of the substrate, a number of processes take place physically, chemically and biologically inside the compost pile simultaneously. In order to seize all those primary phenomena, two main issues have to be taken into account. The first issue is mass and energy balance inside the compost domain and on environmental boundary, which governs how heat and mass (moisture and oxygen) transport simultaneously in the domain, and interact with a specific environmental condition. It is composed of Heat system, Hygro system and Oxygen system (see Fig. 1). The second issue is microbiological activities governing model (named Biomodel hereby). This describes microbial population, growth/death rate, substrate consumption, heat generation, oxygen consumption etc.under a specific environmental condition, which is a result of the mass and energy balance equations.

The analysis system receives necessary initial conditions, such as chemical, physical, and biological characteristics of waste, or substrate, and compost, and sends these data to the ain system, see Fig. 1. The Biomodel then calculates generation and consumption amount of substances according to the Stoichiometric equation of biological decomposition reaction and send the data to the corresponding mass and energy balance system. Temperature, moisture content, and oxygen concentration of the compost domain will be calculated and used as the environmental condition for the calculation of the reaction in the next step. After completion of the analysis, the characteristics of the waste and compost will be returned to the user for further decision making.

***Mass and energy balance equations***

The rate of microbiological activities depends on many growth-limiting factors. Especially, temperature, moisture, and oxygen are the most important factors affecting the reaction rate of the activities. In this section, we proposed mass and energy balance equations for those heat, moisture and oxygen to specify environmental condition at any specific point where environmental sensitive reaction takes place.

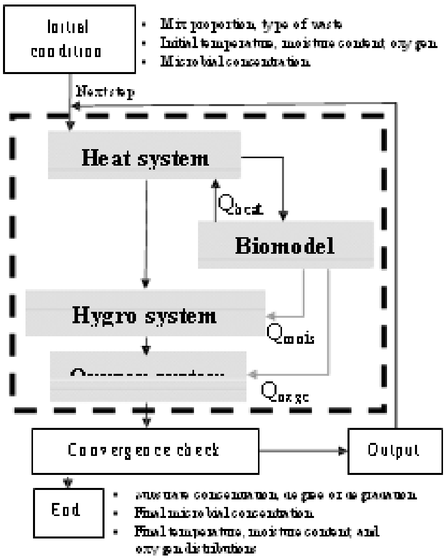


**Fig. 1** Framework of the BioDuCOM.

In composting, moisture distribution caused by movement of liquid water, vapor as well as wetting/drying process contributes large effect to heat transport. This resulted in redistribution of the temperature, which is one of the most sensitive growth-limiting factor for the degradation rate. For that reason, the coupled heat and moisture transport is exceedingly important. The following subsections show the governing equations for coupled heat, moisture, and oxygen transport inside the compost domain, respectively.

*a. Coupled heat transport governing equation*

Heat transport in compost pile and across boundary surface is associated with many transportation modes. This is due to the facts that during composting process, a number of substances simultaneously transports inside and across boundary surface of the compost pile while carrying heat energy together with those substances. As a result, those coupled effects have to be considered in order to get closer to the real phenomena. The governing equation for coupled heat energy together with those substances. As a result, those coupled effects have to be considered in order to get closer to the real phenomena. The governing equation for coupled heat transport proposed in the analysis system is expressed as follows [1, 2].

$$C\frac{\partial T}{\partial t} = -div\left(-D_h \nabla T + \sum_i (T - T_0)\cdot J_i \cdot C_i + H \cdot J_v\right) + Q_{heat} \qquad (1)$$

*C* represents a total volumetric heat capacity of the compost, kJ/m$^3$.K. *T* is temperature in °C. *T0* is a reference temperature in °C, which is equal to temperature of the previous time step. $D_h$ represents a thermal conductivity due to pure molecular diffusion, kJ/m.day.K. $J_i$ is a convective flux as a medium *I* for convective heat transfer, kg/m$^2$.day. The convective flux represents other mediums that can carry heat when it is being transported. These fluxes consist of water vapor, liquid water and other convective gas fluxes. $C_i$ is heat capacity per unit weight of the corresponding convective medium, kJ/kg.K. *H* is latent heat of vaporization or condensation, kJ/kg, for the water vapor flux, $J_v$ in kg/m$^2$.day. Heat generation or absorption by biological activities is represented by *Qheat* , kJ/ m3.day.

### *b. Coupled moisture transport governing equation*

Moisture occupying in the compost pore space possesses two forms: liquid and gaseous phase (vapor). Phase balance between both liquid and vapor depends on pore pressure (matrix potential, $\psi_m$ in meter) and temperature. In compost pile, abruptly changes in mass and energy are treated to have a small effect so that it can be assumed that liquid and vapor are always in a quasi-equilibrium phase, which can be governed by the Kelvin's equation.

Four moisture driven forces are considered in current simulation model: liquid water transport by matrix potential gradient, liquid water transport by temperature gradient, water vapor transport by vapor concentration gradient, and gravitational force. Governing equation of total moisture movement including liquid water movement and water vapor movement within the compost pile follows the modified Klute equation [3], where volumetric moisture content, θ, is a potential term of the equation.

$$\frac{\partial \theta}{\partial \psi_m}\frac{\partial \psi_m}{\partial t} = -div(J_l + J_v) + \frac{\partial k_z}{\partial z} + Q_{mois} \qquad (2)$$

$J_l$ and $J_v$ represent liquid water and water vapor flux, m$^3$/m$^2$.s, respectively. $k_z$ is an unsaturated hydraulic conductivity in vertical direction, m/s. The first term on the right-hand side of eq. (2) represents the net transfer of moisture through an element. The second term refers to the gravitational effect, which is more significant in case of higher water content. The last term, *Qmois*, represents an amount of change in moisture within compost domain (moisture generation by the reaction, water loss/gain by some mean, etc) in (m$^3$/m$^3$)/s.

The liquid water flux, $J_l$, is expressed as,

$$J_l = -(k_\theta \nabla \theta + k_T \nabla T) \qquad (3)$$

$k\ \theta$ is an unsaturated water diffusivity due to moisture gradient, $m^2/s$, and $k$ T due to temperature gradient, $m^2/°C.s$. $T$ is an average temperature of three-phase system of the compost, °C.

The water vapor flux, $J_v$, is derived from original Fick's law, which is a function of vapor concentration gradient, with a number of modifications and enhancement by many researchers. The vapor concentration under specific matrix potential and temperature is governed by Kelvin's equation regarding the phase equilibrium. The equation was simplified so that it can be solved numerically by ignoring less order terms [4]. Consequently, the flux equation as a function of volumetric moisture content gradient and temperature gradient can be expressed as shown in the following equation [5].

$$J_v = -\frac{a \tau \nu D_{va} P_v M^2 \eta}{R^2 T^2} \left[ g \left( \frac{\partial \psi_m}{\partial \theta} \right) \nabla \theta + \frac{H}{MT} \nabla T \right] \qquad (4)$$

$a$ is a volumetric air void fraction, $m^3/m^3$. $\tau$ represents a tortosity factor. Penman [6] suggested 0.66 to be a suitable value for general soil. Rollins [7] introduced a so-called "Mass flow factor", $\nu$, which regards convective flow of vapor with coexistence of air mass. The factor has value very near unit.

$D_{va}$ represents a diffusivity coefficient of vapor in free atmosphere, $m^2/s$. The vapor enhancement factor, $\eta$, is a correction factor when a "Liquid island" phenomenon and correction of air-void temperature gradient are considered [8, 9]. $P_v$ is vapor pressure in Pa. M is a molecular weight of water vapor, kg/mole, which is equal to 0.018 kg/mole. $R$ is the universal gas constant, J/mole.K. $g$ is gravitational acceleration, $m/s^2$.

*c. Oxygen transport governing equation* Total oxygen transport contains two terms: gaseous phase transport and dissolved phase transport. Phase balance is governed by the Henry's law. The governing equation of the total oxygen transport is shown in the following equation [10].

$$\frac{\partial}{\partial t} \left\{ \phi (1-S) \cdot \rho_g + S \cdot \rho_d \right\} = -div(J_{O_2}) + Q_{oxge} \qquad (5)$$

The oxygen flux, $J_{O2}$, contains individual flux of both phases, as expressed in the following equation.

$$J_{O_2} = -\left( D_{dO_2} + D_{gO_2} \cdot K_{O_2} \right) \nabla \rho_d \qquad (6)$$

$\phi$ represents porosity, $m^3/m^3$, of the compost having $S$ as a degree of saturation, $m^3/m^3$. $\rho_g$ is gaseous oxygen concentration, $kg/m^3$, in the pore. Pore liquid contain amount of dissolved oxygen, $\rho_d$, in $kg/m^3$. $D_{dO2}$ and $D_{gO2}$ represent diffusion coefficient of dissolved and gaseous oxygen, $m^2/day$, respectively. $K_{O2}$ is modified Henry's constant. Oxygen consumption and generation rate is represented by $Q_{oxge}$, $kg/m^3.day$.

*d. Mass and energy balance on surface*

The equation that governs mass and energy flowing across the boundary between the compost matrix and ambient environment is expressed as in the following equation.

$$\frac{\partial(-J_{sur})}{\partial n} + Q_{sur} = 0 \tag{7}$$

Mass or energy flux, *Jsur*, flows across the surface having normal vector, *n*. *Qsur* represents mass or energy generation/loss rate at the boundary. The flux *Jsur* is linearly dependent on the difference of energy or mass concentration between inside and outside the surface. The parameter that is controlling an amount of the flow is γ, which controls sensitivity of the mass or energy flowing across the surface, namely transfer coefficient. The flux equations are defined as in the following expressions for the Heat, Hygro, and Oxygen system, respectively.

$$-J_{sur,h} = \gamma_h (T_{env} - T) \tag{8a}$$

$$-J_{sur,\theta} = \gamma_\theta (RH_{env} - RH) \tag{8b}$$

$$-J_{sur,O_2} = \gamma_{O_2} (O_{2,env} - O_2) \tag{8c}$$

The subscript *env* denotes environmental quantity of the corresponding system. *T*, *RH*, $O_2$ represent temperature, relative humidity and oxygen concentration, respectively. Relative humidity can be calculated from the Kelvin's equation.

### *Microbiological activities model*

Modeling the activities of living organism is not a simple task due to complexity of substances, chemical reactions inside and outside microbial cells, existence of various types of microorganism, etc. An engineering approach to these problems is to simplify the real phenomena based on appropriate assumptions. The primary assumptions are; substrate and microbial cells can be expressed by a simple chemical formulation, all microorganisms possess the same growing state, decomposition process obeys a simple Stoichiometric equation [11], and growth rate can be explained by Monod equation. Reaction heat rate is calculated by multiplying the substrate consumption rate by the Gibb's free energy for degradation reaction. Two main equations were introduced to govern the activities. The first is the Stoichiometric equation, which describes balance among cell generation, oxygen consumption, heat generation, substrate and water as well as other gases [12]. The second is growth rate governing equation, the modified Monod equation [13] with consideration of each primary growth-limiting factor. The Stoichiometric equation for aerobic decomposition reaction of the substrate having chemical formulation of *CaHbOcNd* is shown in eq.(9).

$$\begin{aligned} &C_aH_bO_cN_d + 0.5(ny + 2s + r - c)O_2 \rightarrow \\ &nC_wH_xO_yN_z + sCO_2 + rH_2O + (d - nz)NH_3 \end{aligned} \tag{9}$$

Where $r = 0.5(b - nx - 3(d - nz))$, $s = a - nw$. It is assumed

Where $r = 0.5(b - nx - 3(d - nz))$, $s = a - nw$. It is assumed that the substrate is completely oxidized and yields carbon dioxide, water, ammonia, and new microbial cells ($C_wH_xO_yN_z$). The ratio of carbon substance in substrate forming carbon dioxide and new cells depends on the coefficient *n*, the yield factor. Growth of the microbial can be divided into four phases: lag, exponential, stationary, and death phase according to the batch growth theory [14]. The Fig. 2 shows population (cell concentration) of microbial versus time.

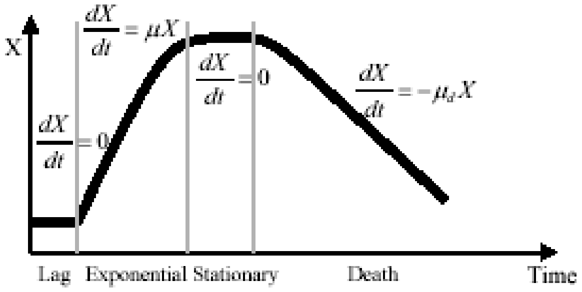


**Fig. 2** Typical growth curve for batch growth.

Growth rate equation that able to simulate the full span length of the batch growth is shown in eq. (10)

$$\frac{dX}{dt} = \alpha\mu X - \beta\mu_d X \qquad (10)$$

*X* represents cell concentration, kg/m$^3$, or cell population. μ is a specific growth rate, sec-1, uring the exponential phase while μ *d* is a specific death rate, sec-1, during the death phase. Due to lack of experimental information, the specific death rate is assumed as a constant regardless to temperature and other factors. α and β are the parameters controlling the active phase among those four phases. It is assumed that the growth rate of microbial during lag and stationary phase is zero. Microbial population starts to increase after the microbial have adapted itself to the surrounding environment. The time required for microbial to adapt itself to ambient environment is called as lag time. In the analysis system, the state of the microbial changes from lag to exponential phase after the time *t* elapsed past the lag time. However, in the analysis the lag time is assumed to be zero for the sake of simplicity. The exponential phase changes to stationary phase once the substrate is depleted. Stationary phase is a time of significant physiological change and particularly involves the physiological adaptation of cells to survival through periods of little growth. After some specific time length under starvation condition (stationary phase length), the microbial state changes to death phase and continues until microbial population reached zero.

The environment-dependent specific growth rate can be expressed as in eq. (11). It depends on temperature, substrate concentration, oxygen concentration, and water content in the linear multiplication form.

$$\mu = f_T(T) \cdot f_S(S) \cdot f_{O_2}(O_2) \cdot f_{H_2O}(\theta) \qquad (11)$$

According to the previous research [15], rate-limiting enzyme can exist in two possible configurations, an active and inactive form in equilibrium with each other. Only active enzymes can activate the reaction. The temperature dependent factors, $f_T(T)$, in eq. (11) can be expressed as in eq. (12).

$$f_T(T) = \left[A_T \cdot e^{-\frac{E_1}{RT}}\right]\left[1 + K_T \cdot e^{-\frac{E_2}{RT}}\right]^{-1} \qquad (12)$$

The first term on right-hand side of eq. (12) represents the original Arrhenius equation, the second terms for enzyme inactivation fraction, or fraction of active enzyme. *AT* is a rate constant, $sec^{-1}$, which is a maximum growth rate when activation energy for growth limiting reaction, $E_1$ (J/mole), become zero or temperature *T*, Kelvin, reached infinite value. The $K_T$ is an enzyme inactivation constant. $E_2$ is an enthalpy change for enzyme inactivation reaction, J/mole. *R* is the universal gas constant in J/mole.K. The eq. (13) represents the substrate limiting factor, which is originally a part of the original Monod equation [13]. *S* is substrate concentration required for growth of microbial ($kg/m^3$). $K_s$ is a substrate limiting constant. The value of $f_s(S)$ reduces the specific growth rate by half when substrate concentration equals to $K_s$.

$$f_s(S) = \frac{S}{K_s + S} \qquad (13)$$

Microbial acquires oxygen for its survival and doing activities from dissolved form in liquid water. The eq. (14) accounts for dissolved oxygen concentration, *O2* (kg/m3), dependent growth rate of the microbial [16].

$$f_{O_2}(O_2) = \frac{O_2}{K_o + O_2} \qquad (14)$$

It is assumed that dissolved oxygen is always in equilibrium with gaseous oxygen. However, in some cases especially when oxygen consumption rate is very high, the rate of decomposition reaction may be limited by dissolving rate of the gaseous oxygen. In this case, oxygen diffusion through water film around the compost particle must be considered. Characteristic of the function is controlled by the oxygen limiting constant $K_o$ as in the substrate limiting factor, eq. (13).

Moisture content is also considered as one of the primary growth rate limiting factors. Microbial requires optimum amount of water content as for transport medium of nutrient and oxygen into the cell through the cell membrane. In this model, an optimum amount of water content is defined as $\theta_{opt}$, minimum and maximum water content required to proceed the reaction are $\theta_{min}$ and $\theta_{max}$, respectively. It is assumed that those critical water contents are linearly related. It is resulted in bilinear relation representing a relationship between water content and growth rate factor having maximum value equal to one at optimum water content.

## Experiment and Analysis

Three series of experiment have been conducted to verify the proposed coupled transport equations and the whole analytical system. The compost type used throughout in this research is a blend of cow and chicken manure and bark. The compost has relatively high porosity (more than 85%) compared to pure cattle manure due to amendment with natural barks. Oven-dried compost (C/N: 19) was mix with fresh water to obtain a compost mix that has 60% water content by weight (or 25.4% by volume). The mix is then packed into a 30x30x30cm (inner dimension) thermal insulated box having closed/opened top lid for studying of coupled mass and energy transport under closed and opened B.C., respectively (see Fig. 3a and 3b). The experiments are named as *Close60%* and *Open60%* respectively. The compost that is used in both heat and moisture transport experiments are oven-dried, in which none of microbial exists. It was assumed that an existence of microbial has no effect on the mass and moisture transfer inside the compost pile. The box is made by assembling wooden plates and then insulated by 1cm thick microporous thermal insulation panel. For the *Close60%* experiment, top of the box is thermally insulated and sealed with cloth adhesive tape to ensure leakage possibility of water vapor thought the box opening. The experiment *Close60%* and *Open60%* had a flexible silicon rubber heater installed at the bottom of the box as for supplying heat energy to the compost mass. The heater supplies heat energy at rate of 0.1612 kcal/m$^2$.s. For the *Close60%* experiment, heat energy is supplied until the compost matrix temperature at the bottom of the box has reached about 75°C, and is then stopped. Temperature measurement was continued for about 24 hours to study heat leakage phase of the box. However, in the *Open60%* experiment, the heater and measurement is stopped when temperature at the bottom has reached about 60°C, no heat leakage phase in this case.

The third experiment was proposed for overall simulation of the most common composting case. Moist compost with a considerable amount of microbial was mixed with waste from potato distilled liquor production (C/N: $\approx$ 7, water content by weight = 87.6%) to obtain a final 60% water content compost mix. The mix is then packed into the same box as used in the previous two experiments under opened B.C. (Imo60%), see Fig. 3c. Experiments having opened B.C., *Open60%* and *Imo60%*, are conducted in a temperature and humidity controlled chamber (temperature = 20°C, and R.H. = 60%). Porosity of the compost used in all experiments is controlled to be about 87%. Temperature distribution at 5cm interval has been recorded (H coordinate starts from the bottom of the box in cm).

Analytical calculations are carried out based on the BioDuCOM with parameters evaluated experimentally to verify properties of the material under various conditions. It is assumed that the volumetric heat capacity of the compost as appeared in eq. (1) is a linear summation of volumetric heat capacity of each phase of the compost (solid, liquid, and gaseous). Density of solid particle and the average heat capacity of dry solid phase of the compost are evaluated experimentally by calorimetric method. Those two parameters have value of 1298.9 kg/m3 and 0.9414 kJ/kg.K, respectively. The temperature and moisture dependent thermal conductivity in eq. (1) in analysis is based on the measurement using nonsteady- state probe. The unsaturated hydraulic conductivity is assumed as 1E-9 m/s [17], and it is independent on temperature and moisture content. However, temperature and moisture content dependent coefficient based on capillary pore structure model will be introduced in further research to obtain a more accurate simulation. The transfer coefficients in eq. (8a) to eq. (8c) are 36000.0, 0.0043, and 6.63 for the Heat, Hygro, and Oxygen system, respectively.

Gibb's free energy for degradation reaction has been carried out by calorimetric method, using a conductive calorie meter, under various environmental conditions. The total heat of reaction released from a mole of substrate (solid phase of the liquor waste) is found to be approximately 2868.3 kJ per mole. The yield factor, $n$, for common bacteria growth is assumed as 0.4. The waste from potato distilled liquor production contains two phases, liquid and solid. The solid phase is mainly protein, fat, fibers, etc. The liquid phase is water mixed with alcohol. Only the solid phase is assumed as biodegradable, i.e. only 12.4% by weight of substrate can be decomposed. For simplicity, chemical formulation of the liquor waste needed in the Stoichiometric equation is assumed as a combination between 80% of protein ($C_{16}H_{24}O_5N_4$) and 20% of fat ($C_{50}H_{90}O_6$), resulted in a simple chemical formulation as $C_{22}H_{37}O_5N_3$. Chemical formulation of the new cell mass (generic bacteria) is given as $C_5H_7O_2N_1$ [11].

The parameters in the temperature dependent factors, $f_T(T)$, are adopted as follows: $E_1$ = 23500.0 J/mole, $E_2$ = 250000.0

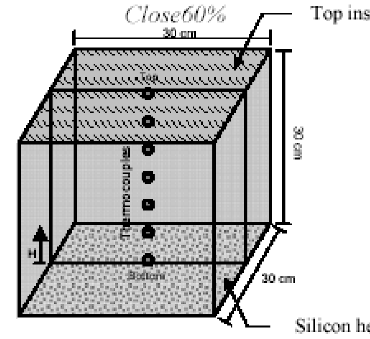


**Fig. 3a** Closed B.C. heater-box configuration.

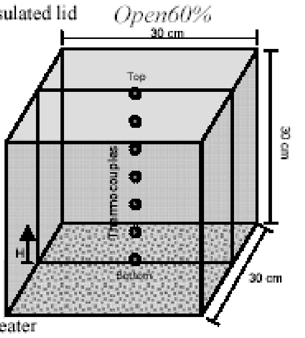


**Fig. 3b** Open B.C. heater-box configuration.

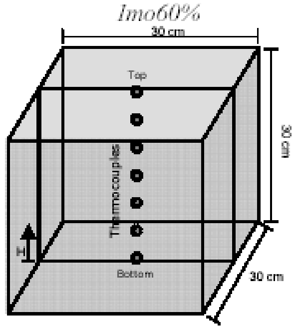
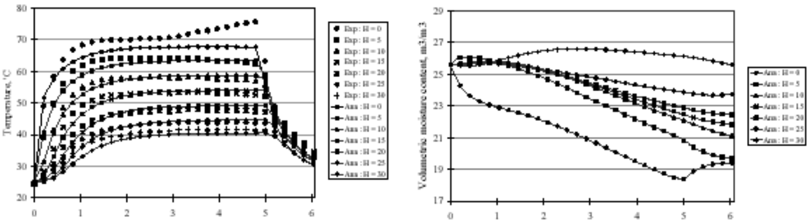


**Fig. 3c** Open B.C. compost-box configuration.

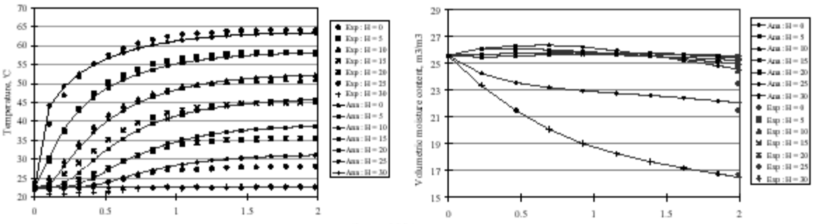
J/mole, $K_T$ = 2.0E+37, $A_T$ =0.1968 sec$^{-1}$. These give the value of $f_T(T)$ maximum at 4.4907E-5 sec$^{-1}$ under approximately 349 K (76°C). Environmental specific death rate $\mu_d$ = 5.787E-7 sec$^{-1.}$ The other parameters for the rest of environmental dependent factors are $K_s$ = 8, $K_o$ = 0.08, $\theta_{min}$ = 4.0%, $\theta_{opt}$ = 25.4%, $\theta_{max}$ = 28.0%. Initial conditions needed for the growth rate equation are calculated as in the following. It is assumed that an amount of bacteria cells per a gram of dry compost is 2.0E+7, and weight of one cell as 1.0E-12 grams. Consequently, initial concentration of the bacteria can be calculated ($X_0$ = 2.54E-3 kg/m$^3$). Initial amount of substrate concentration was calculated from an amount of substrate mixed with compost in the experiment *imo60%*, $S_0$ = 20.67 kg/m$^3$. Initial temperature, moisture content, and oxygen concentration are the same as in the corresponding experiment.

## Result and Discussion

Experimental and analytical results of temperature distribution for the *Close60%* and *Open60%* experiments are



*Close60%*



*Open60%*

**Fig. 4** Experimental and analytical results on temperature and moisture distributions of *Close60%* (upper figures) and *pen 60%* (lower figures).

shown in Fig. 4. The corresponding volumetric moisture distribution for each case is shown on the right. However, due to lack of experimental data on moisture content distributions, only analytical results are shown. For the *Close60%* and *Open60%* experiments, once the heat energy is supplied, temperature of the compost at the location nearest to the heat source was increasing rapidly. Temperature at the higher locations gradually increased while losing heat through the box sides. For the *Close60%* experiment, temperature at almost every locations tended to be stable after approximately one and a half days. This is because the supply heat rate was nearly the same rate as that of the heat loss. After the heat supply was stopped, the heat loss rate also decreased as temperature gradient of the insulation panel decreased. Moisture content at the bottom of the box, H = 0, decreased rapidly to about 18.5% (by volume) at 5 days compared to it initial moisture content. After heater is stopped, water content was increasing by driven force from moisture content gradient and gravity. On the other hand, at the top of the box, H = 30, water content increased after one day due to accumulating of water vapor transported from the lower level. After the heater is turned off, the moisture content was decreased by the same reason as the bottom location. On the other hand, for the *Open60%*, the energy and mass balance on the surface becomes significant. An amount of heat lost through the compost surface is larger than that of the previous case. Similarly, moisture content at the bottom decreased in large extend compare to other locations. However, because the top extend compare to other locations. However, because the top environment, moisture lost through the top surface by drying process is more significant. In this case, small increment in moisture content at the intermediate locations can be observed. This is because water vapor has condensed at lower temperature level before reaching the top surface. Nevertheless, moisture content at these locations gradually decreased due to drying of the upper surface (inducing moisture content gradient), which made the water flux flows upward. Moisture content data at each level of the *Open60%* experiment is measured manually after the experiment finished, at 2 days. Analytical results, the temperature distributions, of both experiments show a good prediction by the proposed coupled mass and energy balance equations. In addition, analytical result of the moisture content distribution for *Open60%* is roughly in a good agreement with the experimental one (only data at the end of the experiment is available).

As for the *Imo60%* experiment, see Fig. 5, order of temperature is reasonably predicted. The reaction is started at about 18.5°C, a number of microbial gradually increased resulted in gradually increasing in heat generation rate. However, while the reaction rate was too slow in the first 5 days, heat lost rate overcame the heat generation rate so that the temperature inside the compost pile increased very slowly. Microbial population exponentially increased and generated faster heat rate that could overcome the heat lost rate within about 5-6 days. Subsequently, temperature of the compost pile increased dramatically until the maximum temperature reached nearly 60°C. Decomposition activities at the depth 15cm below surface seem to be the fastest. Above that level, the activity slows down due to lower temperature as a result from heat loss as well as drying process through the compost surface. Below the 15cm level, oxygen is thought to be a main factor slowing down the degradation rate. At about 8 days, the reaction inside the pile reached the fastest state. Moisture produced from the reaction and pre-existing moisture vaporized at the lower level and condensed at the location near the surface where temperature is lower, causing increment in total moisture content at H = 30. However, the moisture near the surface suddenly dried out which resulted in decrement in moisture content. The Fig. 5 also shows the analytical oxygen concentration distribution for the *Imo60%* experiment. Oxygen concentration correspondingly started to decrease after the reaction rate proceeded.

Based on sensitivity analysis, Gibb's free energy of decomposition and growth rate seems to be main factors affecting overall temperature distribution. Improving more accurate Stoichiometric equation and growth rate equation yields a more accurate analytical result, which bring a possibility to obtain a better and safer composting system.

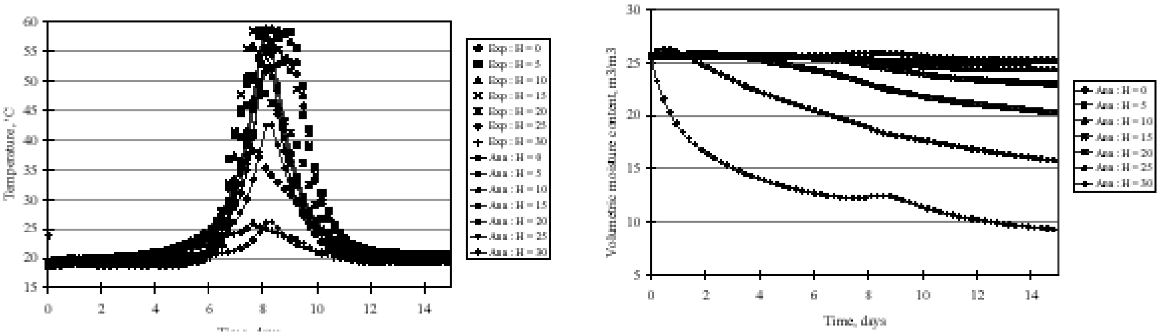


**Fig. 5** Experimental and analytical results on temperature and moisture distributions of *Imo60%*

## Conclusions

In this research, mass-energy balance equations on heat, moisture and oxygen transport, and environmental dependent biological activities governing equations are integrated into FEM analysis system, which lead to a possibility for optimized designing of the composting system. According to the obtained results, the analytical results showed an acceptable agreement to simulate the composting behavior.

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