A NUMERICAL MODELING OF COMPOSTING PROCESS WITH AERATION

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ABSTRACT
A mathematical model has been proposed for numerical simulation of composting processes under aeration controls. Upon exploiting the local volume averaging theory, an appropriate set of governing equations has been introduced so as to describe complex transport phenomena associated with microbe species, substrates and water in composting operations. A two-dimensional numerical experiment has been conducted to reveal the temporal and spatial variations of the system temperature, substrates and microbial concentrations within an open channel type composting system, aerated by forced ventilation. The effects of mechanical agitation on the composting process have been also investigated in terms of temperature and concentrations over the pile cross-section.

INTRODUCTION
According to Huang (1993), composting is the biological decomposition and stabilization of organic substrates under such conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land. Composting is an ancient art, yet, engineering, which requires even a skilled man to resort to a handbook supported by empiricism. Such a handbook approach with little scientific knowledge, practicing today, invites those in the field of porous media to challenge developing a mathematical model and numerical simulation tool based on it. Using such a simulation tool, we may predict the composting process and eventually to improve the operation control.

A typical composting reactor is shown in Figure 1, where the air is ventilated from the bottom. Mathematical modeling of composting processes in such a reactor is still in its infancy. Some attempts (Jenkins 2003, Kaiser 1996, Das and Keener 1997, Li and Glowinski 1996, Fujita 1998, Nakayama et al. 2006) have been successfully made to simulate the composting reactions. However, in all these models, only single representative temperature and mass concentrations in the reactor are in consideration. Their spatial distributions have never been taken into account. Nakasaki et al. (1987) proposed a novel model based on a lumped parameter system to assess optimal operations for drying of composting substrates. They stress that the aeration rate and reaction temperature are the two leading factors for controlling the water vaporization rate in the wet substrates. It would be essential to know the spatial distributions of the quantities of interest within the reactor if we are to search a possible optimal operation condition for the aeration control.

In this study, we introduce the volume-averaging theory previously established for the study of porous media with heat generation (e.g. Nakayama et al. 2001), and try to extend it to establish a complete set of the volume-averaged governing equations appropriate for the analysis of composting processes. Since they are derived from first principles, the resulting set of the
volume-averaged equations can describe both temporal and spatial details of composting processes under various aeration operations. As a first step towards our strategic efforts to establish a complete numerical prediction tool for composting operations, we combine two individual energy equations for the gas and solid to form a single energy equation for the reactor temperature. This one energy equation model has been tested for both temporal and spatial prediction of composting processes subject to aeration control. The volume-averaged differential equations, thus established for numerical simulation of composting processes with aeration have been implemented in the program code SAINTS (Nakayama 1995) based on SIMPLE algorithm. A series of calculations were carried out for an open channel type composting system ventilated from the bottom. Both temporal and cross-sectional variations of the system temperature, substrate and microbe concentrations are compared against available data to elucidate the validity of the present differential model for the composting operation.

VOLUME AVERAGED SET OF GOVERNING EQUATIONS

It is certainly beneficial to model a composting system, in which biological stabilization and conversion processes take place, as a porous medium filled with substrate, microbes, water, vapor and other uncompostable substances. For many years, the concept of local volume-averaging theory, namely, VAT, has been extensively used to investigate momentum, heat and mass transport processes associated with porous media. The theory is quite relevant since only macroscopic characteristics are of practical interest in most engineering applications. In order for the volume averaging (smoothing process) to be meaningful, we consider a local control volume \( V \) in a porous medium filled with substances, whose length scale (say \( V^{1/3} \)) is much smaller than the macroscopic characteristic length (say the size of the reactor), but, at the same time, much greater than the microscopic matrix characteristic length, namely, the grain size of the composting substances (see e.g. Nakayama 1995). Under this condition, the volume average of a certain variable \( \phi \) in the gas phase is defined as

\[
\langle \phi \rangle = \frac{1}{V} \int_V \phi dV
\]  

(1)

Another average, namely, the intrinsic average, is given by

\[
\langle \phi \rangle = \frac{1}{V_f} \int_{V_f} \phi dV
\]  

(2)

where \( V_f \) is the volume space which the gas occupies. Obviously, two averages are related as

\[
\langle \phi \rangle = \varepsilon \langle \phi \rangle
\]  

(3)

where \( \varepsilon = V_f / V \) is the free air space (namely, FAS or void fraction rather than the porosity, since the volume occupied by the liquid is not included in \( V_f \). The superscripts \( f \) and \( s \) refer as to the gas and the rest, respectively. Thus, the other intrinsic average within the matrix phase may be defined by

\[
\langle \phi \rangle = \frac{1}{V_s} \int_{V_s} \phi dV
\]  

(4)

The composting matrix consists of three phases, namely, solid, liquid and gas. The solid phase includes biodegradable substrate, microbes, humic substances converted from dead organisms and minerals, whereas the main contents of the gas phase are oxygen, nitrogen, carbon dioxide and water vapor. Both substrate and microbes are of multi-components. However, we shall consider a composting system of one defined substrate and one defined microbe species and exploits the concept of local volume-averaging theory based on two distinctive phases. For simplicity and definiteness, let the one phase (gas phase, denoted by the super- and subscripts \( f \)) refer as to the mixture of air and water vapor, and the other phase, namely, the porous matrix (denoted...
by the super- and sub-scripts $s$, refer as to the liquid water, biodegradable substrate, microbe and uncompostable substances, all of which are assumed to be in thermal equilibrium within the matrix. Note that we consider only two distinctive intrinsic average temperatures, namely, one for the gas $T_f$ and the other for both solid and liquid $T_s$. It would be straightforward to follow Nakayama et al. (2001) and obtain the set of the volume averaged governing equations which runs as

\[
\frac{\partial (\rho_f + \rho_w)}{\partial t} + \frac{\partial \rho_f \langle u_i \rangle}{\partial x_i} = 0
\]

(5)

\[
1 \frac{\partial \rho_f \langle u_i \rangle}{\partial t} + \frac{\partial \left( \rho_f \langle u_i \rangle - \mu_f \frac{\partial \rho_f}{\partial x_i} \right)}{\partial x_i} = -\frac{\partial \langle \rho_f \rangle}{\partial x_i} - \frac{\mu_f}{K} \langle u_i \rangle
\]

(6)

\[
\rho_f \varepsilon_r \left( \frac{\partial \langle T_f \rangle}{\partial t} + \langle u_i \rangle \frac{\partial \langle T_f \rangle}{\partial x_i} \right) + \frac{1}{V} \int_{V_f} \varepsilon_r \langle T_f \rangle \, dV_f
\]

(7)

\[
\rho_w \varepsilon_r \left( \frac{\partial \langle T_f \rangle}{\partial t} + \langle u_i \rangle \frac{\partial \langle T_f \rangle}{\partial x_i} \right) = \frac{1}{V} \int_{V_f} \varepsilon_r \langle T_f \rangle \, dV_f
\]

(8)

\[
\frac{\partial \langle W \rangle}{\partial t} + \frac{\partial \langle W \rangle}{\partial x_i} = -\frac{1}{V} \int_{V_f} \varepsilon_r \langle W \rangle \, dV_f + \frac{1}{V} \int_{V_f} \varepsilon_r \langle W \rangle \, dV_f
\]

(9)

\[
\frac{1}{V} \int_{V_f} \varepsilon_r \langle W \rangle \, dV_f + \frac{\partial \langle S \rangle}{\partial t} = \frac{1}{V} \int_{V_f} \varepsilon_r \langle W \rangle \, dV_f
\]

(10)

where

\[
\rho_w = \frac{1}{\rho_f} \left( \rho_{w v} c_{p,v} + \langle W \rangle c_{p,water} + \langle S \rangle c_{p,substrate} \right)
\]

(11a)

and

\[
\rho_f = \rho_{water} + \langle W \rangle + \langle S \rangle
\]

(12a)

is the density of the gas mixture while

\[
\rho_{water} = \left(1 - \varepsilon\right) \left( \langle W \rangle + \langle X \rangle + \langle S \rangle + \langle U \rangle \right)
\]

(12b)

is the apparent density for the solid and water mixture, in which $\langle W \rangle$, $\langle S \rangle$, $\langle X \rangle$ and $\langle U \rangle$ are the intrinsically averaged concentrations of the water, substrate, microbe and uncompostable substances, respectively. During the bio-degradation, some of the substrate $\langle S \rangle$ consumed by the microbes converts into organisms, whereas the other reacts with oxygen and converts into carbon dioxide in the respiration activity (corresponding to $\langle S \rangle$). The modeling of the respiration activity, however, is out of the scope of this study, since our main purpose here is to establish a numerical model for revealing both temporal and spatial variations of the quantities of interest, such as local temperature, and water concentration, in order to seek a possible optimization of aeration control.

Note that $\langle u_i \rangle$ is the volume average velocity, which is the apparent velocity, often referred to as Darcian velocity. Assuming the flow in the matrix to be laminar, Darcy’s law is introduced with the permeability $K$. The effective thermal conductivity for the gas phase, which accounts for molecular diffusion, tortuosity and mechanical dispersion, is denoted by $\varepsilon k_{\varepsilon_f}$ while that for the solid and water is denoted collectively by $(1 - \varepsilon) k_{w_s}$. The constants $H_w$ and $H_s$ appearing as a heat source in the energy equation (8) are the latent heat of water vaporization and the heat released metabolically, respectively. The heat transfer between the gas and matrix is described by the second right hand side term in the energy equation (8) (also the second right hand side term in (7)) where $A_{int}$ is the interface area within $V$, and $n_j$ is the unit vector outward normal from the gas side to matrix side. Similarly, the mass transfer from the matrix to gas is taken into account by the second right hand side term in the mass transfer equation (9) (also the second right hand side term in (10)). Furthermore, $\varepsilon D_{\varepsilon_f}$ and $(1 - \varepsilon) D_{w_s}$ are the effective diffusion coefficients for the gas mixture and matrix, respectively.

The microbial growth rate is modeled according to Contois:

\[
\frac{\partial \langle X \rangle}{\partial t} = -\mu \langle W \rangle - k_{\text{growth}} \langle X \rangle
\]

(13)

where $\mu$ is the maximum specific growth rate is given by...
The foregoing model for the microbial growth rate is illustrated in Figure 2. The microbial growth rate coefficient \( \mu \) (which should not be confused with the air viscosity \( \mu_A \)) increases suddenly, as the water mass fraction \( (1-\varepsilon)\left(W/W_0\right) / \rho_w \) within the wet matrix exceeds a certain value \( w_a \), attains its maximum at \( (1-\varepsilon)\left(W/W_0\right) / \rho_w = w_i \), and then decreases linearly to vanish at \( (1-\varepsilon)\left(W/W_0\right) / \rho_w = w_e \). The coefficient \( \alpha \) accounts for the empirical evidence found by Nakasaki et al. (1985) that \( \mu \) increases with the temperature following Arrhenius expression up to 60 degree centigrade (i.e. \( T_M = 60 \) degree centigrade), but decreases sharply for any further temperature rise, as microbial activities are held back. \( E_A \) and \( R_A \) in Arrhenius expression are the activation energy and gas constant, respectively. Fujita (1998) and Nakayama et al. (2006) recommends the values as follows:

\[
K_a = 0.04, \quad w_a = 0.15, \quad w_i = 0.6,
\]
\[
w_e = 0.8, \quad T_M = 60^\circ C, \quad T_e = 80^\circ C
\]

Furthermore, the multiplicative constant \( \mu_k \) depends no the degradability of the composting material. \( k_i \) is the Contios constant which is related to the growth yield as \( k_i Y = 4 - 20 \). Note that the endogenous respiration is neglected. Here, we assume \( k_i = 24 \), \( Y = 0.5 \) and \( \mu_k = 0.18/hr. \)

**DERIVATION OF ONE-ENERGY EQUATION MODEL**

The set of foregoing volume averaged equations is quite formidable since there are many unknown dependent variables. We may simplify the problem greatly, upon noting that the density of the gas mixture \( \rho_f \) is almost constant such that the continuity and momentum equations reduce to:

\[
\frac{\partial}{\partial t} \left( \rho_f u \right) + \frac{\partial}{\partial x} \left( \rho_f u u \right) = - \frac{\partial p}{\partial x} + \mu_T \frac{\partial^2 u}{\partial x^2}
\]

Thus, for given \( \rho_f \), the flow field subject to forced ventilation may be established independently. Nakayama et al. (2001) investigated the temperature field within a porous slab with heat generation with the solid phase and analytically showed \( \langle T' \rangle = \langle T \rangle \) as long as the macroscopic characteristic length scale (i.e. the size of the reactor) is much greater than \( \sqrt{k_f / h_s} \) where \( h_s \) is the volumetric heat transfer coefficient. Thus, upon combining the two energy equations (7) and (8), we have

\[
\left(\chi_\omega^w + \rho_f c_p \chi_\omega^w \right) \frac{\partial \langle T' \rangle}{\partial t} + \rho_f c_p \frac{\partial \langle T' \rangle}{\partial x} + \frac{\partial}{\partial x} \left( \rho_f c_p u \langle T' \rangle \right) = \frac{1}{\rho_f} \left( \mu_T \frac{\partial^2 \langle T' \rangle}{\partial x^2} \right)
\]

Figure 2: Microbial growth rate
Note that the second right hand side terms are cancelled out. The mass transfer equations (9) and (10) for the water vapor and liquid water require additional modeling for closure, which may result in

\[
\frac{\partial (W_i')}{\partial t} = \frac{\partial}{\partial x_j} \left( D_i \frac{\partial (w_i')}{\partial x_j} \right) - a_i h_i \left( \frac{w_i'}{w_i} + |x_j|^2 + |x_j|^2 \right) \left( (w_i')_{\text{sat}} - (w_i') \right)
\]

\[
(1-\varepsilon) \frac{\partial (W_i')}{\partial t} = \frac{\partial}{\partial x_j} \left( (1-\varepsilon) D_i \frac{\partial (W_i')}{\partial x_j} \right) + a_i h_i \left( \frac{w_i'}{w_i} + |x_j|^2 + |x_j|^2 \right) \left( (w_i')_{\text{sat}} - (w_i') \right)
\]

The interfacial mass transfer terms in these equations have been modeled as

\[
\frac{1}{V} \int D_i \frac{\partial W_i'}{\partial x_j} dA = - \frac{1}{V} \int D_i \frac{\partial (w_i')}{\partial x_j} dA
\]

where we estimate the saturated water vapor concentration \( (W_i')_{\text{sat}} \) using the local temperature \( (T_i') \) as

\[
(W_i')_{\text{sat}} \left( (T_i') \right) = 0.804 \left( \frac{p_{\text{sat},i}/p_{i}}{1-\left( p_{\text{sat},i}/p_{i} \right)} \right) \exp \left( \frac{-3994}{11.96 - \left( T_i' + 233.9 \right)} \right) \left[ \text{kg/m}^3 \right]
\]

which is Antoine’s correlation. The transport equations (16), (17), (18) (19) and (20) for \( (u_i) \), \( (p_i') \), \( (T_i') \), \( (W_i') \) and \( (W_i')' \) may be solved along with the auxiliary equations (13) (along with (14) and (15)) and (22). The total mass of the composting material \( m(t) \) may be calculated as

\[
m(t) = \int_{x_{\text{min}}}^{x_{\text{max}}} (\rho_a + \rho_i) dV = \int_{x_{\text{min}}}^{x_{\text{max}}} \rho_i dV
\]

\[
(1-\varepsilon) \int_{x_{\text{min}}}^{x_{\text{max}}} \left( (W_i')' + (X_i)' + (S_i)' + (U_i)' \right) dV
\]

**NUMERICAL MODEL AND ITS INITIAL AND BOUNDARY CONDITIONS**

We consider a composting process within an open channel type (bin type) with its cross-sectional area 3m x 6m as already shown in Figure 1. The channel is long enough for the problem to be two-dimensional. The air continuously flows into the channel from the bottom by forced ventilation and the exhaust gas escapes from the top exposed to the ambient air. The sidewalks of the channel are thermally insulated, whereas the bottom wall is maintained at a constant temperature. The initial and boundary conditions appropriate for the problem are as follows:

**Initial conditions:**

\[
\{u\} = \{v\} = 0 \text{ m/s}, \quad \{W_i\} = 600 \text{ kg/m}^3
\]

\[
\{T_i\} = \{T_i'\} = 20^\circ C, \quad \{X_i\} = 10 \text{ kg/m}^3
\]

\[
\{S_i\} = 300 \text{ kg/m}^3, \quad \{U_i\} = 90 \text{ kg/m}^3
\]

**Boundary conditions:**

Bottom of the bin \( (y=0 \text{ m}) \):

Case 1: Uniform flow over the bottom surface:

\[
\{v\} = 3 \text{ mm/s}, \quad \{u\} = 0 \text{ mm/s}
\]

Case 2: Slot areas for aeration:

\[
\{v\} = 2.5 \text{ cm/s}, \quad \{u\} = 0 \text{ cm/s}, \quad \text{otherwise, } \{u\} = \{v\} = 0 \text{ cm/s}
\]

Both cases

\[
\{T_i\} = 20^\circ \text{C and } \{W_i\} = \frac{\partial (W_i')}{\partial y} = 0
\]

Sidewalls (Adiabatic and impermeable walls):

\[
\{u\} = \{v\} = 0 \text{ cm/s}, \quad \frac{\partial (T_i')}{\partial y} = 0, \quad \frac{\partial (W_i')}{\partial y} = 0
\]

Top surface of the bin \( (y=3 \text{ m}) \):

\[
\frac{\partial (v)}{\partial y} = \{u\} = 0
\]

\[
-(\epsilon k_p + (1-\varepsilon) k_a) \frac{\partial (T_i')}{\partial y} = h \left( (T_i') - T_a \right)
\]

\[
\phi (W_i') = 0
\]

\[
\{W_i'\} - (1-\varepsilon) D_i \frac{\partial (W_i')}{\partial y} = \{W_i\} \left( 1-\varepsilon \right) \frac{\partial (W_i')}{\partial y}
\]

The subscript \( a \) stands for the ambient air such that \( T_a \) and \( h_a \) are the ambient temperature and heat transfer coefficient. The last boundary condition for the liquid water is set such that it, when the transport equations (19) and (20) are integrated over the entire reactor system, conforms to the empirical water-air rate
relationship obtained by Fujita (1998), namely,

\[
\frac{dm_w}{dt} = -W_{sat} \dot{V}_{air} \frac{m_w}{m_{sat}}
\]

where \(m_w\), \(W_{sat}\) and \(\dot{V}_{air}\) are the total mass of the water within the system, the concentration of the saturated water vapor corresponding to the system temperature and the volume flow rate of the dry air supplied by forced ventilation.

As for a reference case, we consider a composting process within the same static pile as investigated by Fujita (1998), in which the air continuously flows into the static pile from the bottom by forced ventilation and the exhaust gas escapes from the top exposed to the ambient air. The volume of the static pile is 235.5 m^3 and the initial total mass \(m_{sat}\) = 47100 kg such that the apparent density is 200 kg/m^3. The other values needed for initiating computations are listed as follows:

Reference case:
\[
K_w = 0.04, \ w_i = 0.15, \ w_1 = 0.6, \ w_2 = 0.8, \ T_{air} = 60 \degree C ,
\]
\[
T_i = 80 \degree C, \ E_g = 29kJ/mol, \ R_g = 8.314J/molK, \ k_e = 24,
\]
\[
Y = 0.5, \ V = 235.5m^3, \ V_{air} = 0.262m^3/s,
\]
\[
\varepsilon = 0.8, \ \rho_{air} = 1.20 \ kg/m^3, \ c_{air} = 1400 \ J/kgK,
\]
\[
c_w = 4200 \ J/kgK, \ c_{sub} = c_x = c_a = 2100 \ J/kgK,
\]
\[
H_w = 2.44x10^6 J/kg and H_{sub} = 1.76 x10^7 J/kg, \ T_s = 20\degree C,
\]
\[
\mu = 0.18/hr \ (i.e. 5x10^{-5} / s), \ \h = 8.2W / m^2K \ (i.e. h_A = 640W/K), \ k_p = 0.024W/mK, \ k_{se} = 0.16W/mK,
\]
\[
D_w = 2x10^{-5} m^2/s, \ D_x = 5x10^{-6} m^2/s, \ a_{se}h_D = 10^4 W/m^3K.
\]

Initial conditions:
\[
m = 47100 kg, \ m_w = 28260 kg, \ m_{sub} = 14130 kg and
\]
\[
m_{sat} = 471 kg, \ \rho_{sat} = 200 kg / m^3, \ such \ that
\]
\[
(1-\varepsilon)(W^0) / \rho_{sat} = 0.6, \ (1-\varepsilon)(S^0) / \rho_{sat} = 0.3 \ and
\]
\[
(1-\varepsilon)(X^0) / \rho_{sat} = 0.01, \ (1-\varepsilon)(U^0) / \rho_{sat} = 0.09,
\]
\[
\varepsilon_c = (W^0 / c_x + (S^0 + (X^0 + (U^0) / c_{sat})(1-\varepsilon) / \rho_{sat}) = 3.36kJ/kgK
\]

RESULTS AND DISCUSSION

The steady velocity field is established within two hours of aeration. The steady velocity field predicted by the present model is shown in Figure 3 for the case in which air is supplied from two air slots located on the bottom surface (i.e. Case 2). The velocity field around the air slots appears quite complex as recirculation bubbles are formed. However, these fluid motions subside within the pile and almost uniform upward velocity field is established closed to the upper surface.

The values of the effective diffusion coefficient for the liquid water \(D_w\) and interfacial mass transfer coefficient \(a_{se}h_D\) (which should be determined experimentally) are not available in the literature. The results, however, are found fairly insensitive to either \(D_w\) or \(a_{se}h_D\). (Note that too large \(D_w\) or \(a_{se}h_D\) leads to unrealistically oscillating solutions.) Therefore, tentative values as listed above are set for a series of calculations.

The temporal development of the system temperature averaged over the entire volume is illustrated in Figure 4. The system temperature rises steeply to reach its maximum around 70 degree Celsius after 40 hrs of aeration. Since the microbial growth rate
drops sharply after 60 degree Celsius as illustrated in Figure 2, the heat generation ceases and the temperature stays around 70 degree Celsius, before it gradually decreases.

The detailed fields of temperature, liquid water, microbes and substrate obtained after 15 days of aeration are shown in Figures 5 to 8.

It is seen from Figure 5, that a low temperature region extends from the bottom of the reactor because of comparatively strong aeration. The bio-reactions generate heat as the air penetrates through the matrix and form a high temperature region towards the top. Figure 6 clearly shows that the liquid water evaporates from the top surface and thus, the concentration in the pile is stratified.

The similarity between the contours of microbes and substrate is obvious from Figures 7 and 8, since the microbes grow as they consume the substrate. The microbes are seen most active around the air slots where both temperature and liquid water concentration are moderate, namely, 60 degree Celsius and 60%, respectively, which gives the peak microbial growth rate.

The aeration should be controlled such that the temperature and water concentration, say, as closely as 60 degree centigrade and 60%, respectively, so as to accelerate the composting process. The present numerical model may be exploited to seek such an optimal condition.

As a first attempt for such a numerical trial, the calculations are conducted to investigate the effects of mechanical agitation (stirring) on the composting process. We shall assume that all microbes, substrate and liquid water within the pile are mixed completely after a certain interval. During such mechanical agitation, substantial amount of heat will be released from the pile to environment, while the porosity may decrease with water concentration within the pile.

Figures 9 and 10 show the contours of temperature and substrate, when the volume of the pile decreases down to about 80%. As the top surface lowers, the cooling by the ambient air intensifies to a certain degree, as illustrated in Figure 9. This cooling creates moderate temperature spots near the top surface where microbial growth rate is high.
Correspondingly, the contour pattern of substrates becomes quite complex, as shown in Figure 10.

Finally, the system temperature and the total amount of substrate, when mechanical agitation is applied repeatedly, are plotted in Figures 11 and 12 for several values of Stanton number for mechanical agitation ($St = hA/c_1 m_{st}$, where $m_{st}$ (kg/s) is the stirring rate). The temperature drops abruptly for each mechanical agitation, and rises steeply again to reach its maximum. This sequence is repeated again and again. Naturally, the higher the Stanton number, the lower the system temperature. The substrate concentration decreases more for higher Stanton number, since the system temperature drops below the optimum temperature 60 degree Celsius and at the same time, all substances are distributed evenly within the pile by mechanical mixing, all which works favorably for activating microbes. However, excessive heat loss may decelerate the composting process as indicated in Figure 12 for the case of large Stanton number.

CONCLUSIONS

A mathematical model accounting for the system heat balance, water transport and microbial growth rate has been proposed for numerical simulation of composting processes under aeration controls. The volume averaging theory developed in the field of porous media has been successfully applied to derive the macroscopic set of governing equations for transport phenomena associated with microbe species, substrate and water in composting operations. A series of two-dimensional numerical calculations have been conducted to reveal the temporal and spatial variations of the system temperature, substrate and microbial...
concentrations within an open channel type composting system, aerated by forced ventilation. The effects of mechanical agitation on the composting process have been also investigated in terms of temperature and concentrations over the pile cross-section.

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