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# Estimation of vertical air flow in passively aerated compost in a cylindrical bioreactor

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<sup>2</sup>*Bioresource Engineering Department, McGill University, 2111 Lakeshore Road, Ste-Anne-de-Bellevue, Quebec H9X 3V9, Canada; and* <sup>3</sup>*Agricultural, Food and Nutritional Science, AF 4-10, University of Alberta, Edmonton, Alberta T6G 2P5, Canada. \*Email: grant.clark@mcgill.ca*

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Yu, S., Clark, O.G. and Leonard, J.J. 2008. **Estimation of vertical air flow in passively aerated compost in a cylindrical bioreactor.** *Canadian Biosystems Engineering/Le génie des biosystèmes au Canada* **50**: 6.29–6.35. Passive aeration systems are often more economical than active aeration systems and can deliver similar performance, but mathematical descriptions of the process are inadequate for use in design or optimization. Therefore, a practical analytical model of air flow through passively aerated compost in a cylindrical bioreactor was developed. The model relates the physical characteristics and temperature of the compost with the predicted passive, convective air flow. The effect of compaction on the permeability of the compost was considered in the application of the model. The model was evaluated using temperature time series data from a passively aerated composting experiment as inputs, and the calculated air flow rates were not significantly different from the measured values ( $p=0.97$ ). **Keywords:** compost, passive aeration, air flow, analytical model.

Les systèmes d'aération passive sont souvent plus économiques que les systèmes d'aération active tout en étant en mesure de fournir des performances comparables. Cependant, les descriptions mathématiques des processus d'aération passive ne sont généralement pas adéquates pour permettre la conception ou l'optimisation de tels systèmes. Dans le but de remédier à cette lacune, un modèle analytique pratique a été développé afin de prédire l'écoulement de l'air à travers un bioréacteur cylindrique contenant du compost aéré de manière passive. Le modèle fait le lien entre les caractéristiques physiques et la température du compost lorsque ce dernier est soumis à un écoulement d'air convectif passif tel que déterminé par ce modèle. L'effet de la compaction sur la perméabilité du compost a été pris en compte dans l'élaboration du modèle. Le modèle a été évalué en utilisant comme données de base des séries temporelles de températures provenant d'une étude de compostage sous aération passive. Les débits d'air déterminés par le modèle n'ont pas été significativement différents des débits mesurés expérimentalement ( $p=0,97$ ). **Mots clés:** compost, aération passive, écoulement d'air, modèle analytique.

## INTRODUCTION

Composting is generally defined as the aerobic degradation of organic matter by microorganisms under controlled conditions. Aeration is critical in composting because it supplies oxygen, and removes carbon dioxide, excess heat and moisture from the compost (Haug 1993). The benefits of composting, for example, high degradation

rate, low odor generation, and efficient space utilization, cannot be achieved without appropriate aeration. Composting systems can be categorized into two types according to the aeration strategies employed: actively aerated systems and passively aerated systems. In actively aerated systems, mechanical means are used to draw or blow air through the compost, whereas in passively aerated systems the driving force is natural convection resulting from temperature differences (Fogiel et al. 1999).

Passive aeration systems are more economical than active aeration systems in terms of initial capital investment, operation, maintenance, and operator training costs (Haug 1993). Passive and forced aeration systems have been shown to result in similar process rates (Fernandez and Sartaj 1997) and compost quality (Solano et al. 2001), and both can be operated in cold climates (Lynch and Cherry 1996a; McCartney and Eftoda 2005).

Mathematical descriptions of passively aerated compost systems, however, are very limited, probably due to the focus of the research interest. Actively aerated systems, however, have been well described mathematically (Haug 1993). The lack of an adequate mathematical description of heat and mass transfer in passively aerated compost makes such systems difficult to predict and control. Effective system design and optimization is also difficult, which is a barrier to the adoption of passively aerated composting. One critical obstacle to modeling passively aerated systems is a mathematical description of air flow. In actively aerated systems, air flow rate is described by pumps or fans. As a result, the supply of oxygen to the compost and the removal of carbon dioxide, ammonia, heat, and moisture can be estimated with reasonable accuracy. In passively aerated systems, however, the air flow rate is driven by natural convection. Natural convective air flow is difficult to estimate accurately without an appropriate mathematical model because it is often relatively small and highly variable (Yu et al. 2005).

The more general problem of natural convection through porous media has been extensively studied in other areas of research, and this work has been well summarized by Nield and Bejan (1999). Attention has focused on specific configurations such as homogenous porous media adjacent to regular-shaped heating sources or natural convection within enclosed porous media

(Nield and Bejan 1999). Passively aerated composting, however, usually takes place in an open system with a very heterogeneous, self-heating substrate, making it very difficult to adopt any of the mature theories summarized by Nield and Bejan (1999).

An alternative is to start with a simple analysis to illustrate the mechanisms involved. Lynch and Cherry (1996b) proposed the first analytical model for the description of air flow through passively aerated compost, employing Darcy's law to estimate the vertical velocity of air through the porous compost pile. The model was based on the understanding that natural convection is driven by buoyancy derived from a temperature gradient. The influence of the substrate permeability was discussed in detail, and windrow geometry was included as a model parameter. Evaluation of the model using measured data was not demonstrated in the paper, however, possibly because of the difficulty of air flow measurement in actual windrow composting systems.

Barrington et al. (2003) took advantage of classical heat and mass transfer theory. The measured temperature and psychrometric properties of the air were used to calculate the Grashof number (Geankoplis 1993), and a relationship between the Grashof number and the measured air flow rates at outlet was determined empirically using least-squared regression. The relationship between the Grashof number and the air flow rate was found to be linear or quadratic, depending on the structural characteristics of the substrate. No theoretical explanation of the nature of this relationship was proposed.

### Objectives

The objectives of this work were: (1) to derive a practical mathematical model that can accurately predict the air flow through passively aerated compost in a cylindrical bioreactor. This is required for system design and optimization; and, (2) to evaluate the developed model by comparing air flow rates calculated using experimental temperature data with measured air flow rates at inlet.

Criteria for model development included: (a) the model should accurately portray the underlying physical processes; (b) the values of the input variables required to use the model should be easy to measure; and (c) the effect of compaction of the material on its permeability during composting should be considered in the application of the model.

## MODEL DEVELOPMENT

### Physical model

The physical model used in this study consisted of dairy manure and straw composted in an enclosed, insulated, passively aerated cylindrical composting vessel, 0.9 m in height and 0.6 m in diameter. An aeration plenum was created using an expanded metal floor installed 0.10 m from the bottom of the vessel. As demonstrated in previous work (Lynch and Cherry 1996b; Barrington et al. 2003), convective air flow is the primary mode of oxygen supply in passively aerated systems. The cylindrical physical model selected for this study embodies the

key feature of convective air flow, which is the vertical movement of the air due to buoyancy.

### Conceptual model

The compost bed in the vessel was considered by the model to consist of layers, each having homogeneous physical and chemical properties (Fig. 1). Microbial activity in each layer consumed oxygen ( $O_2$ ) and released carbon dioxide ( $CO_2$ ), heat, and moisture ( $H_2O$ ). The air flow through the compost was considered to be uniform and unidirectional from bottom to top, removing heat, moisture, carbon dioxide, and volatile compounds.

The following assumptions were made for the development of the model equations:

1. Each layer was physically and chemically homogeneous in all respects.
2. Air was incompressible.
3. Air entered the bottom layer of compost uniformly, and air flow was uniform through each layer.
4. The mass flow rate of dry air was constant throughout the compost bed. The influence of oxygen consumption and carbon dioxide generation were negligible.
5. Air traveled through the compost bed in the vertical direction only.
6. The temperature of the air leaving each layer was the same as the substrate in that layer.

To be practical, a model should be able to predict the air flow rate given the values for a set of easy measurable input variables. Since natural convection derives from a temperature difference, and air temperature can be easily measured compared with most other variables (Barrington et al. 2003), temperature was incorporated into the model as an input. Other inputs included the permeability of the substrate, and the temperature and density of the ambient

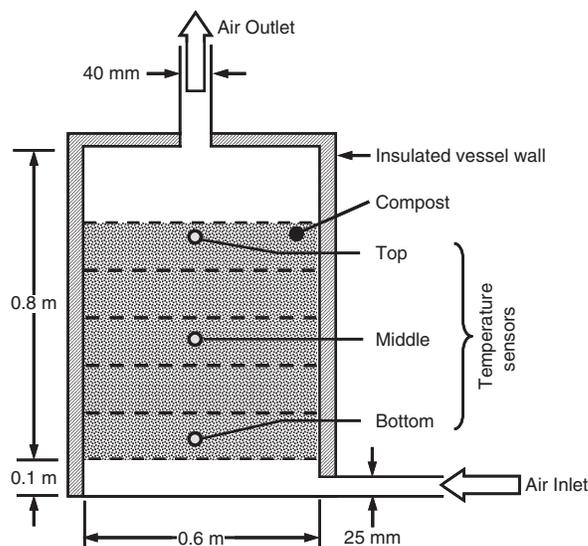


Fig. 1. Schematic of the physical model of passively-aerated compost.

air. Based on the assumptions made in this work, the Ideal Gas Law and Archimedes' Principle were used to relate the temperature difference between the ambient air and the air in the compost bed to the buoyant force acting on the air. The derivation of this part of the model is detailed in the following section.

### Analytical model of passive air flow: Fundamentals

In the simplest case, passive convection occurs when a fluid of constant viscosity and negligible compressibility is subjected to a temperature gradient. The creeping flow of an incompressible fluid through a porous medium (the compost) can be described by Darcy's law. Darcy's law is applicable when the Reynolds number (Re) is less than 1 (Eq. 1) (Nield and Bejan 1999).

$$\text{Re} = \frac{\rho v \sqrt{K}}{\mu} \quad (1)$$

The buoyant force that drives the air flow is calculated using Archimedes' Principle: the buoyant force is equal to the weight of the displaced fluid. Given constant pressure, the change of volume of a unit of ideal gas is related to the change of temperature as shown in Eqs. 2 and 3:

$$\frac{V_0}{T_0} = \frac{V_i}{T_i} \quad (2)$$

$$V_0 = \frac{T_0}{T_i} V_i \quad (3)$$

The temperature of actively degrading compost is higher than ambient. In this model, the temperature of the air in the compost bed when it exits a given layer is assumed to be the same as that of the substrate in that layer, so that as a unit of air passes through the  $i$ th layer in the compost it will undergo isobaric expansion from  $V_0$  to  $V_i$ . The forces on this amount of air are described by Eqs. 4–6.

$$F_{\text{Buoyancy}} = \rho_0 g V_i \quad (4)$$

$$G = \rho_0 g V_0 \quad (5)$$

$$\begin{aligned} F_i &= F_{\text{Buoyancy}} - G = \rho_0 g (V_i - V_0) \\ &= \rho_0 g \left(1 - \frac{T_0}{T_i}\right) V_i \end{aligned} \quad (6)$$

Compost can be viewed as a porous medium and Darcy's law is used to calculate average air velocity through the compost (Eq. 7) for the sake of simplicity.

$$v = -\frac{K \Delta P}{\mu \Delta y} \quad (7)$$

Assuming the volume of air in the  $i$ th layer ( $V_i$ ) has a height ( $H_i$ ) that is the same as the thickness of the layer ( $\Delta y$ ), and an effective cross-sectional area ( $A_i$ ) that includes only that of the empty pore space in the compost,

the pressure gradient over the thickness of the layer can be estimated from the net force distributed over the effective cross-sectional area (Eq. 8). Substituting the last term in Eq. 6 for  $F_i$  in Eq. 8 and dividing the two sides of the equation by  $\Delta y$  (or the equivalent term  $H_i$ ) gives Eq. 9.

$$\Delta P = F_i / A_i \quad (8)$$

$$\frac{\Delta P}{\Delta y} = \left[ \rho_0 g \left(1 - \frac{T_0}{T_i}\right) V_i / A_i \right] / H_i = \rho_0 g \left(1 - \frac{T_0}{T_i}\right) \quad (9)$$

Finally, substituting the simplified form of Eq. 9 for the ratio denoting the pressure gradient in Eq. 7 gives Eq. 10.

$$v = -\frac{K \Delta P}{\mu \Delta y} = -\frac{K}{\mu} \rho_0 g \left(1 - \frac{T_0}{T_i}\right) \quad (10)$$

### Model inputs

To apply the proposed model (Eq. 10), values for substrate permeability, air viscosity, temperature and density of ambient air, and temperature in the compost are required. The viscosity of air is well understood and well-developed theory can be readily employed to calculate the changing dynamic viscosity at different locations in the compost. The permeability of the composting material is a critical factor in the development of air flow, and the influence of substrate composition on the permeability is quite complex. A theoretical relationship between the geometry of the substrate particles and the permeability of the substrate has been described elsewhere (Lynch and Cherry 1996b). The application of this relationship is limited, however, since the measurement of the required parameters is not easy. Another approach is to use published results to estimate permeability, while also taking into account the effect of compaction. Since the determination of the permeability of the composting substrate was not the objective of this work, the latter approach was used, and is discussed further later in this paper. The temperature of the ambient air and the compost are convenient to measure. With measured values for the temperature and relative humidity of the air, the density of the air can be calculated using psychrometric relationships (ASHRAE 2001).

### Changing substrate permeability: Compaction

As shown in Eq. 10, the permeability of the substrate is required to predict the air flow rate. Neither the exact substrate permeability values nor the compaction of the compost were measured directly in this study. Instead, the permeability values were estimated from published results that relate measured values of bulk density, moisture content, and initial free air space. The effect of compaction was also considered in this estimate.

First, the compressive stresses at different depths were estimated using Eq. 11 (McCartney and Chen 2001) from initial bulk density values measured using a pycnometer

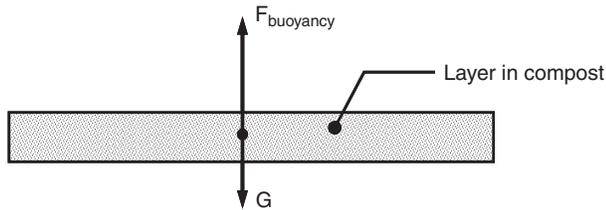


Fig. 2. Schematic of the forces on the air in a single compost layer.

(Agnew et al. 2003). Variation of initial bulk density with depth was not considered for the sake of simplicity

$$\sigma_i = \rho_s g d / 1000 \quad (11)$$

Second, the resultant compaction at different depths was evaluated using Eq. 12 (Das and Keener 1997).

$$h_i = h_{\infty} + \Delta h_0 \cdot \exp(-\beta \cdot \sigma_i) \quad (12)$$

The result of Eq. 12,  $h_i$ , gives the thickness of the  $i$ th layer after compaction as a fraction of the initial thickness of the layer. The actual free air space (FAS) in the  $i$ th layer (Eq. 13) was then predicted using the initial free air space ( $FAS_0$ ), measured with a pycnometer (Agnew et al. 2003).

$$FAS_i = FAS_0 \cdot h_i \quad (13)$$

Richard et al. (2004) presented a relationship between FAS and the permeability of the substrate at different substrate moisture contents. This relationship was used to estimate permeability at different depths given the estimated FAS values from Eq. 13 and the measured moisture content.

#### Evaluation of the proposed model: Experimental data

Evaluation of the model (Eq. 10) was done using data from a composting trial. The trial was conducted in a passively aerated, insulated polyethylene vessel, with an aeration plenum under an expanded metal floor, an inlet pipe and an outlet pipe (Fig. 1). The compost consisted of fresh dairy manure and bulking agents, i.e., wood chips, saw dust, and air-dried, ground straw. Moisture content and C:N ratio were tested followed methods recommended by TMECC (Thompson et al. 2002) and the mixture had a carbon to nitrogen ratio of 35:1 and an initial moisture content of 76% (wet basis). Initial bulk density and free air space values were measured using a pycnometer developed by Agnew et al. (2003), and the mixture had 57% free air space and a bulk density of 520 kg/m<sup>3</sup>. At the beginning of the experiment, the depth of the compost in the vessel was 0.50 m. Temperatures at different positions above the aeration plenum were recorded by an automated data logging system and the air flow rates were measured with smoke tracer and ultrasonic air flow meters (Yu et al. 2005).

The measured bulk density, initial moisture content, and free air space were used to estimate the permeability following the methodology discussed previously (Eqs. 11–13). The measured temperatures of the ambient air and the

compost were used to predict the average air velocity using Eq. 10. SAS software version 9.1 (SAS Institute, Inc. 2006) was used for statistical analysis. A mixed model was employed to test for significant differences between the calculated results and the measured data to evaluate the performance of the proposed model.

## RESULTS and DISCUSSION

The average ambient temperature was 23.3°C ± 2.2°C. The temperature histories at three locations in the compost are shown in Fig. 3. Temperature histories in the middle of the compost followed a form typical of aerobic composting, increasing exponentially to more than 55°C and then gradually declining to about 40°C. The vertical temperature gradient in the compost (Fig. 3) was the result of heat and mass transfer processes, which are strongly related to the local microbial activity in the substrate (Yu et al. 2005). As described previously, the temperature of the air in the compost was assumed to be the same as measured substrate temperature (Fig. 3).

The substrate permeability values were not measured directly but estimated using published results, as summarized previously. The measured initial bulk density was 520 kg/m<sup>3</sup>, so that Eq. 11 can be written as:

$$\sigma_i = 520 \times 9.8 \times d / 1000 \quad (14)$$

Substituting the depth values into Eq. 14 gave the corresponding compressive forces.

The compressive force was substituted into Eq. 12 together with coefficient values ( $h_{\infty}$ ,  $\Delta h_0$ , and  $\beta$ ) estimated using the data reported by Das and Keener (1997), and the measured substrate moisture content (76%). These substitutions resulted in Eq. 15, which was used to estimate the compression of each layer.

$$h_i = 0.586 + 0.141 \cdot \exp(-0.114 \cdot \sigma_i) \quad (15)$$

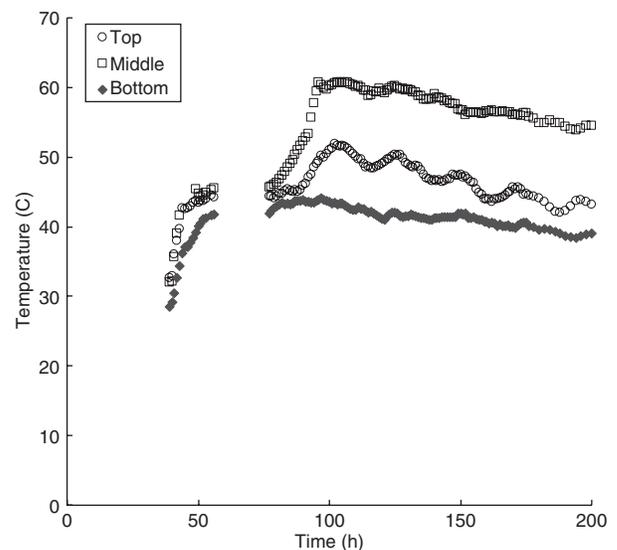


Fig. 3. Temperature histories in the bottom, middle, and top of the compost bed.

The free air space ( $FAS_i$ ) at each layer after compaction was then calculated using the measured initial free air space ( $FAS_0=0.57$ ) (Eq. 13). A total of 5 layers were used in the model, each assumed to be 0.10 m thick. The compression and free air space at different depths were estimated as shown in Table 1. Finally, the permeability at different depths was estimated from Fig. 4 in Richard et al. (2004) with the calculated free air space values and initial moisture content.

The measured and modeled air flow rates through the compost are shown in Fig. 4. The measured air flow rate followed the general pattern of temperature change typical of composting, peaking at about 100 h and then gradually declining, illustrating the temperature-driven nature of the convective air flow. The peak air flow rate measured was  $11.1 \pm 5.1$  mg dry air per s per kg initial dry matter (mg d.a.  $s^{-1} kg^{-1}$  i.d.m.). In comparison, Barrington et al. (2003) reported air flow rates from 1.5 to 0.7 mg d.a.  $s^{-1} kg^{-1}$  i.d.m. in passively aerated compost, and Liang et al. (2004) used a flow rate of 5.6 mg d.a.  $s^{-1} kg^{-1}$  i.d.m. in an actively aerated vessel. The calculated air flow rate followed a similar trend to, and was not significantly different from, the measured data ( $p=0.97$ ).

As shown in Fig. 4, the measured air flow rates varied considerably. This could have been due partly to the limitations of the instrumentation (Yu et al. 2005), partly to environmental factors such as wind gusts over the laboratory building and turbulent ventilation air flow within the laboratory, and partly to the complexity of the composting process. Since composting is a highly heterogeneous process, it is not unusual to see such variation in experimental data and the determination of trends in key parameter values is often the best that can be achieved when experimenting under such circumstances. This work focused on air flow through the compost mixture because resistance to air flow entering and leaving the bioreactor has been reported elsewhere (Yu et al. 2005) and was shown to be negligible.

The assumptions under which this model was developed are very idealized: the air was assumed to be an ideal gas and the mass of the air was assumed to be constant through the compost bed. Phenomena such as the evaporation of moisture from the substrate, volatilization

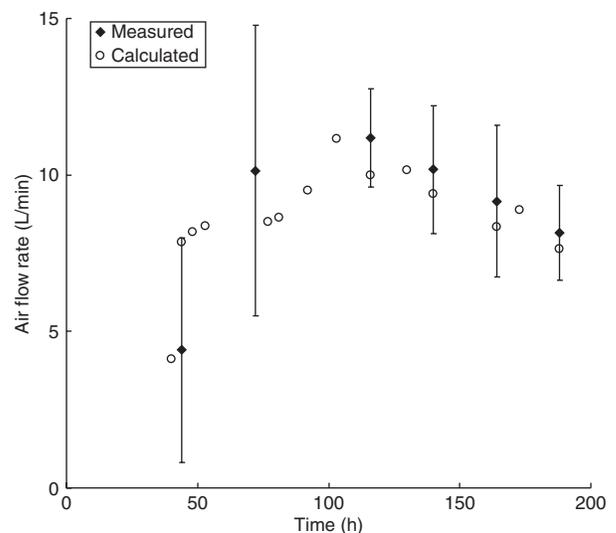
**Table 1. Calculated compressive stress, compression, and free air space (FAS) at different depths. Compression is expressed as the ratio of the thickness of an incremental layer to its initial thickness. Free air space is expressed as a fraction of total volume in an incremental layer.**

Depth (m)	Stress (kPa)	Compression	FAS
0.0	0.00	1.000	0.571
0.1	0.51	0.976	0.557
0.2	1.02	0.948	0.541
0.3	1.53	0.922	0.526
0.4	2.04	0.898	0.513
0.5	2.55	0.875	0.500

of the substrate, consumption of oxygen, and release of carbon dioxide by microbial activity were not considered. In reality, however, these processes do occur during composting, and further research is required to quantify and model their effect on convective air flow development.

Another possible improvement of the model would be to incorporate effects of drag on air flow, using a term such as the Dupuit-Forcheimer relationship (Lage and Antohe 2000; Richard et al. 2004). The current use of Darcy's law, in which only viscous resistance to air flow is considered, is appropriate for the low-rate, laminar flows observed in small-scale, passively aerated systems. Larger-scale systems are more likely to develop higher flow rates, however, and resistance due to drag would become more dominant. Relationships based on the physical characteristics of the substrate might also be used to estimate air flow parameters such as permeability (Ergun 1952; Richard et al. 2004). Finally, the accurate measurement of the air velocity through the compost bed is required for the verification of any model. Measuring air flow in passively aerated compost is more challenging than in actively aerated systems, since air velocity is typically lower, variable, and influenced by the microbial activity in the compost. As pointed out elsewhere (Yu et al. 2005), the instrument used for such measurements must be effective and accurate over a wide range and introduce little pressure loss. Accurate air flow measurement in passively aerated compost is an area that must be better developed in order to effectively validate models such as the one presented here.

The permeability of the substrate is another critical variable that must be accurately determined to improve the accuracy of models. Measurements of permeability have been done mainly under forced aeration (Das and Keener 1997; Richard et al. 2004). It is generally assumed that all the void space in the substrate is filled with air and



**Fig. 4. Measured and calculated air flow rates through the compost. Error bars indicate the standard error of two measurements with an ultrasonic air flow meter ( $n=2$ ).**

that air is free to move through all of that space. As pointed out elsewhere, however, some void space in the composting substrate may not be available for air flow development (Eftoda and McCartney 2004). Moreover, considering the heterogeneous and compressible nature of compost, it is very likely that some of the air in the void space does not move with the air flow. A model of such "unsaturated" air flow might therefore be considered in further research to improve the prediction of average air velocity through compost.

## CONCLUSIONS

Passively aerated composting systems have generally proved to be more economical than active aeration systems, while delivering similar performance, but mathematical descriptions of such systems are scarce, hindering the design and optimization of the process. A model was proposed to address a critical factor in modeling passively aerated systems: the air flow development. Based on the use of a cylindrical bioreactor, the model was developed to relate the physical characteristics and temperature of the compost with the predicted air flow, and the compaction that occurred during composting was also taken into account in the application of the model. The model was evaluated using temperature histories from a passively aerated composting experiment to predict air flow, and the calculated air flow values were not significantly different from measured values ( $p = 0.97$ ).

The model proposed can only be applied to systems with the same configuration as presented in this article: an enclosed cylindrical bioreactor with an aeration plenum at the bottom and exhaust from the top. It cannot be used for triangular and/or trapezoidal shaped windrows directly. Although the underlying theory is the same (i.e., the air flow is driven by buoyancy force) different geometries will require different considerations when deriving the model equations and the results will be different.

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Yu, S., O.G. Clark and J.J. Leonard. 2005. Airflow measurement in passively aerated compost. *Canadian Biosystems Engineering* 47: 39–45.

## LIST of SYMBOLS

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$\beta$	rate of volume reduction
$\mu$	fluid dynamic viscosity of the air ( $\text{N s m}^{-2}$ )
$\rho_o$	density of ambient air ( $\text{kg m}^{-3}$ )
$\rho_i$	density of the air in the $i^{\text{th}}$ layer ( $\text{kg m}^{-3}$ )
$\rho_s$	initial bulk density of substrate ( $\text{kg m}^{-3}$ )
$\sigma_i$	compressive stress at the $i^{\text{th}}$ layer (kPa)
$A_i$	cross-sectional area of the unit air in the $i^{\text{th}}$ layer of compost ( $\text{m}^2$ )
$d$	depth in compost (m)
$D$	diameter of the vessel (m)
$FAS_0$	measured initial free air space ( $0 \sim 1$ )
$FAS$	actual free air space ( $0 \sim 1$ )
$F_{\text{buoyancy}}$	buoyancy force on the air in the $i^{\text{th}}$ layer (N)
$F_i$	net force on the air in the $i^{\text{th}}$ layer (N)
$g$	unit of acceleration due to earth's gravity ( $9.8 \text{ m s}^{-2}$ )
$G$	gravitational force on the air in each layer due to earth's gravity (N)
$\Delta h_0$	total compressible fraction
$h_\infty$	maximum compressed state
$h_i$	fraction of the initial thickness of $i^{\text{th}}$ layer due to compaction effect
$H_i$	height of the unit air in $i^{\text{th}}$ layer of compost with cross-sectional area $A_i$ (m)
$i$	index number of the compost layer (dimensionless)
$K$	permeability of the compost ( $\text{m}^2$ )
$\Delta P/\Delta y$	pressure gradient through the compost ( $\text{Pa m}^{-1}$ )
$T_0$	temperature of ambient air (K)
$T_i$	temperature of the air in the $i^{\text{th}}$ layer of compost (K)
$v$	average air velocity ( $\text{m s}^{-1}$ )
$V_0$	volume of air in the $i^{\text{th}}$ layer of compost with ambient temperature ( $\text{m}^3$ )
$V_i$	volume of air in the $i^{\text{th}}$ layer of compost ( $\text{m}^3$ )

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