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Airflow in Passively Aerated Compost

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Abstract: Passive aeration systems are more economical than active aeration systems and deliver similar performance, but mathematical descriptions of the process are inadequate for use in design or optimization. Therefore, a practical analytical model of airflow development in passively aerated compost 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 verified using temperature time series data from a passively aerated composting experiment as inputs, and the calculated results were not significantly different from the measured values (p = 0.97).

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, p261). The benefits of composting, e.g. high degradation rate, low odour 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, while 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 airflow. In actively aerated systems, airflow rate is prescribed 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 airflow rate is driven by natural convection. Natural convective airflow 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 (Nield and Bejan 1999, chapter 5) or natural convection within enclosed porous media (Nield and Bejan 1999, chapter 6, 7). 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 airflow though 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. Verification of the model was not demonstrated in the paper, however, possibly because of the difficulty of airflow 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 airflow rate was determined empirically using least-squared regression. The relationship between the Grashof number and the airflow 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.

Objective

A practical mathematical model that can accurately predict the airflow development in passively aerated composting systems is required for system design and optimization. The model should accurately portray the underlying physical processes and the values of the input variables required to use the model should be easy to measure. The effect of compaction of the material on its permeability during composting should be considered in the application of the model. The objective of this work was to derive such a model and to test it using experimental temperature and airflow data.

Model development

Physical model

The physical model used in this study consisted of dairy manure and straw composted in an enclosed, insulated, passively aerated 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 airflow 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 airflow, which is the vertical movement of the air due to buoyancy.

Conceptual model

The compost bed in the vessel was considered to consist of layers, each having homogeneous physical and chemical properties (Figure 1). Microbial activity in each layer consumed oxygen (O_2) and released carbon dioxide (CO_2), heat, and moisture (H_2O). The airflow 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 airflow 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 airflow 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 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 airflow: 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 (Equation 1) (Nield and Bejan 1999).

$$\mathrm{Re} = \frac{\rho v \sqrt{K}}{\mu} \tag{1}$$

The buoyant force that drives the airflow 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 Equations 2 and 3:

$$\frac{V_0}{T_0} = \frac{V_i}{T_i} \tag{2}$$

$$V_0 = \frac{T_0}{T_i} V_i \tag{3}$$

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 Equations 4-6.

$$F_{Bouyancy} = \rho_0 g V_i \tag{4}$$

$$G = \rho_0 g V_0 \tag{5}$$

$$F_i = F_{Buoyancy} - G = \rho_0 g (V_i - V_0) = \rho_0 g \left(1 - \frac{T_0}{T_i}\right) V_i \tag{6}$$

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

$$v = -\frac{K}{\mu} \frac{\Delta P}{\Delta y} \tag{7}$$

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 (Δy), 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 (Equation 7.5). Substituting the last term in Equation 6 for F_i in Equation 7.5 and dividing the two sides of the equation by Δy (or the equivalent term H_i) gives Equation 8.

$$\Delta P = F_i / A_i \tag{7.5}$$

$$\frac{\Delta P}{\Delta y} = \left[\rho_0 g \left(1 - \frac{T_0}{T_i} \right) V_i \Big/ A_i \right] \Big/ H_i = \rho_0 g \left(1 - \frac{T_0}{T_i} \right) \tag{8}$$

Finally, substituting the simplified form of Equation 8 for the ratio denoting the pressure gradient in Equation 7 gives Equation 9.

$$v = -\frac{K}{\mu} \frac{\Delta P}{\Delta y} = -\frac{K}{\mu} \rho_0 g \left(1 - \frac{T_0}{T_i} \right) \tag{9}$$

Model inputs

To apply the proposed model (Equation 9), 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 airflow, 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 relatively humidity of the air, the density of the air can be calculated using psychrometric relationships (ASHRAE 2001).

Changing substrate permeability: Compaction

As shown in Equation 9, the permeability of the substrate is required to predict the airflow 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.

Firstly, the compressive stresses at different depths were calculated using Equation 10 (McCartney and Chen 2000) from bulk density values measured using a pycnometer (Agnew et al 2003).

$$\sigma_i = \rho_s g d / 1000 \tag{10}$$

Secondly, the resultant compaction at different depths was evaluated using Equation 11 (Das and Keener 1997).

$$h_i = h_\infty + \Delta h_0 \cdot \exp(-\beta \cdot \sigma_i) \tag{11}$$

The result of Equation 11, 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 (Equation 12) was then predicted using the initial free air space (FAS_0), measured with a pycnometer (Agnew et al 2003).

$$FAS = FAS_0 \cdot h_i \tag{12}$$

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 Equation 12 and the measured moisture content.

Verification of the proposed model: Experimental data

Verification of the model (Equation 9) 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 (Figure 1). The compost consisted of fresh dairy manure and bulking agents, i.e. wood chips, saw dust, and air-dried, ground straw. The mixture had a carbon to nitrogen ratio of 35:1, 57% free air space, a bulk density of 520 kg/m^3, and an initial moisture content of 76% (wet basis). 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 airflow rate was 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 (Equation 10-12). The measured temperatures of the ambient air and the compost were used to predict the average air velocity using Equation 9. SAS 9.1 (SAS Inc., 2006) was used for statistical analysis and mixed model was employed for significant difference test of 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 Figure 3. Temperature histories in the middle of the compost followed a form typical of aerobic composting, increasing exponentially to more than 55ºC and then gradually declining to about 40ºC. The vertical temperature gradient in the compost (Figure 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 (Figure 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^3, so that Equation 10 can be written as:

$$\sigma_i = 520 \times 9.8 \times d / 1000 \tag{13}$$

Substituting the depth values into Equation 13 gave the corresponding compressive forces.

The compressive stress was substituted into Equation 11 together with coefficient values (h_∞, Δh_0, and β) estimated using the data reported by Das and Keener (1997), and the measured substrate moisture content (76%). These substitutions resulted in Equation 14, which was used to estimate the compression of each layer.

$$h_i = 0.586 + 0.141 \cdot \exp(-0.114 \cdot \sigma_i) \tag{14}$$

The free air space (*FAS*) at each layer after compaction was then calculated using the measured initial free air space ($FAS_0 = 0.57$) (Equation 12). Finally, the permeability of different depths was estimated from Figure 4 in Richard *et al*. (2004) with the calculated free air space values and initial moisture content.

The measured and modeled airflow rates through the compost are shown in Figure 4. The measured airflow rate followed the general pattern of temperature change typical of composting (Figure 4), peaking at about 100 h and then gradually declining, illustrating the temperature-driven nature of the convective airflow. The peak airflow rate measured was 11.1 ± 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 airflow 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 airflow rate followed a similar trend to, and was not significantly different from, the measured data ($p = 0.97$).

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 and volatilization 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 airflow development.

Another possible improvement of the model would be to incorporate effects of drag on airflow, using a term such as the Dupuit-Forcheimer relationship (Richard et al. 2004, Lage and Antohe 2000). The current use of Darcy's law, in which only viscous resistance to airflow 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 airflow parameters such as permeability (Richard et al. 2004, Ergun 1952). Finally, the accurate measurement of the air velocity through the compost bed is required for the verification of any model. Measuring airflow in passively aerated compost is more challenging than in actively aerated systems, since the airflow is variable and is 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 airflow 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 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.

Summary and conclusions

In summary, passively aerated composting systems have proven 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 airflow development. The model was developed to relate the physical characteristics and temperature of the compost with the predicted air flow, and the compaction which occurs during composting was also taken into account in the application of the model. The model was verified by using temperature histories from a passively aerated composting experiment to predict airflow, and the calculated airflow values were not significantly different from measured values ($p = 0.97$).

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References

Agnew, JM, JJ Leonard, J Feddes, and Y Feng. 2003. A modified air pycnometer for compost air volume and density determination. *Canadian-Biosystems-Engineering*. 45(6): 27-35

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). 2001. Psychrometrics. In *Handbook of Fundamentals*, ed. ASHRAE, 6.1-6.17. Atlanta, GA: ASHRAE.

Barrington, S, D Choiniere, M Trigui, and W Knight. 2003. Compost convective airflow under passive aeration. *Bioresource technology*. 86 (3): 259-266

Das, K, and HM Keener. 1997. Moisture effect on compaction and permeability in composts. *Journal of environmental engineering – ASCE* 123 (3): 275-281

Eftoda, G, and D McCartney. 2004. Determining the critical bulking agent requirement for municipal biosolids composting. *Compost science & utilization.* 12 (3): 208-218

Ergun, S. 1952. Fluid flow through packed columns. *Chem. Eng. Prog*. 48: 89-94

Fernandez, L and M Sartaj. 1997. Comparative study of static pile composting using natural, forced and passive aeration methods. *Compost Science & Utilization*. 5(4): 65-77

Fogiel, AC, RD von Bernuth, FC Jr. Michel, and TL Louden. Experimental verification of the natural convection transfer of air through a dairy manure compost media. *Proceedings of the International Meeting of the American Society of Agricultural Engineers*; ASAE, St. Joeseph, MI: 1999; ASAE paper no. 994053

Geankoplis, CJ. 1993. Transport processes and unit operations. 3rd ed. Prentice Hall, Engelwood Cliffs, N.J. 921p

Haug, RT. 1993. The Practical Handbook of Compost Engineering. Boca Raton. Lewis Publishers. 717p

Lage, JL and BV Antohe. 2000. Darcy's experiments and the deviation to nonlinear flow regime. *ASME J. Fluids Eng*. 122: 619-625

Lynch, NJ and RS Cherry. 1996a. Winter composting using the passively aerated windrow system. *Compost Science & Utilization* 4(3):44-52

Lynch, NJ and RS Cherry. 1996b. Design of passively aerated compost piles: vertical air velocities between pipes. *Biotechnology Progress* 12(5):624–629

McCartney, D and HT Chen. 2001. Using a biocell to measure effect of compressive settlement on free air space and microbial activity in windrow composting. *Compost science & utilization*. 9 (4): 285-302

McCartney, D and G Eftoda. 2005. Windrow composting of municipal biosolids in a cold climate. *Journal of environmental engineering and science*. 4 (5): 341-352

Nield, DA and A Bejan. 1999. Convection in porous media. 2nd ed. Springer, New York. 546p.

Richard, TL, AHM Veeken, V de Wilde, and HVM Hamelers. 2004. Air-filled porosity and permeability relationships during solid-state fermentation. *Biotechnology progress*. 20 (5): 1372-1381

Solano ML, F Iriarte, P Ciria, and MJ Negro. 2001. Performance Characteristics of Three Aeration Systems in the Composting of Sheep Manure and Straw. *Journal of Agricultural Engineering Research*. 79(3): 317-329

Yu, S, OG Clark, and JJ Leonard. 2005. Airflow measurement in passively aerated compost. *Canadian biosystems engineering*. 47(6): 39–45

List of symbols

β	Rate of volume reduction
μ	Fluid dynamic viscosity of the air ($m^2\ s^{-1}$)
ρ_0	Density of ambient air ($kg\ m^{-3}$)
ρ_i	Density of the air in the i^{th} layer ($kg\ m^{-3}$)
ρ_s	Initial bulk density of substrate ($kg\ m^{-3}$)
σ_i	Compressive stress at the i^{th} layer (kPa)
A_i	Cross-sectional area of the unit air in the i^{th} layer of compost (m^2)
d	Depth in compost (m)
D	Diameter of the vessel (m)
FAS_0	Measured initial Free Air Space (0~1)
FAS	Actual Free Air Space (0~1)
F_i	Net force on the air in the i^{th} layer (N)
g	unit of acceleration due to earth's gravity ($9.8m\ s^{-2}$)
Δh_0	Total compressible fraction
h_∞	Maximum compressed state
h_i	Fraction of the initial thickness of i^{th} layer due to compaction effect
H_i	Height of the unit air in i^{th} layer of compost with cross-sectional area A_i (m)
i	Index number of the compost layer (dimensionless)
K	Permeability of the compost (m^2)
$\Delta P/\Delta y$	Pressure gradient through the compost ($Pa\ m^{-1}$)
T_0	Temperature of ambient air (K)
T_i	Temperature of the air in the i^{th} layer of compost (K)
v	Average air velocity ($m\ s^{-1}$)
V_i	Volume of air in the i^{th} layer of compost (m^3)

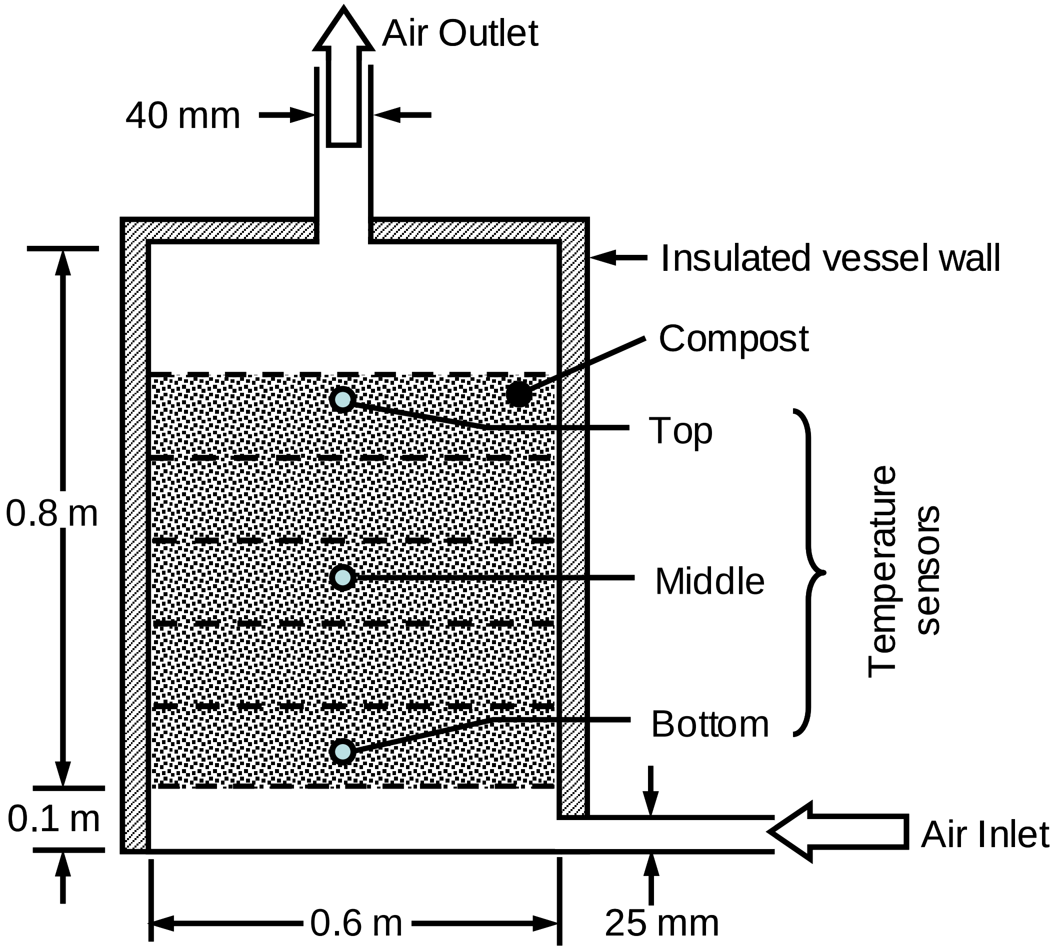
Figure Captions

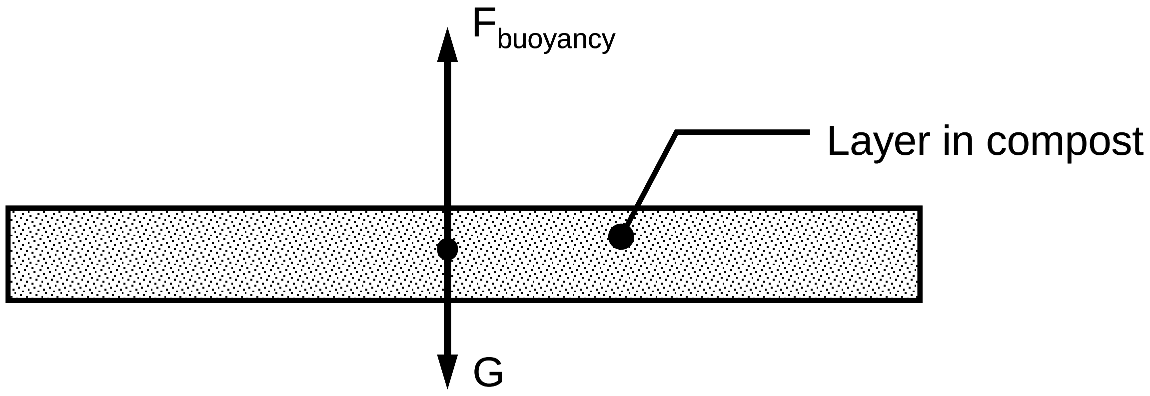
Figure 1. Schematic of the physical model of passively-aerated compost

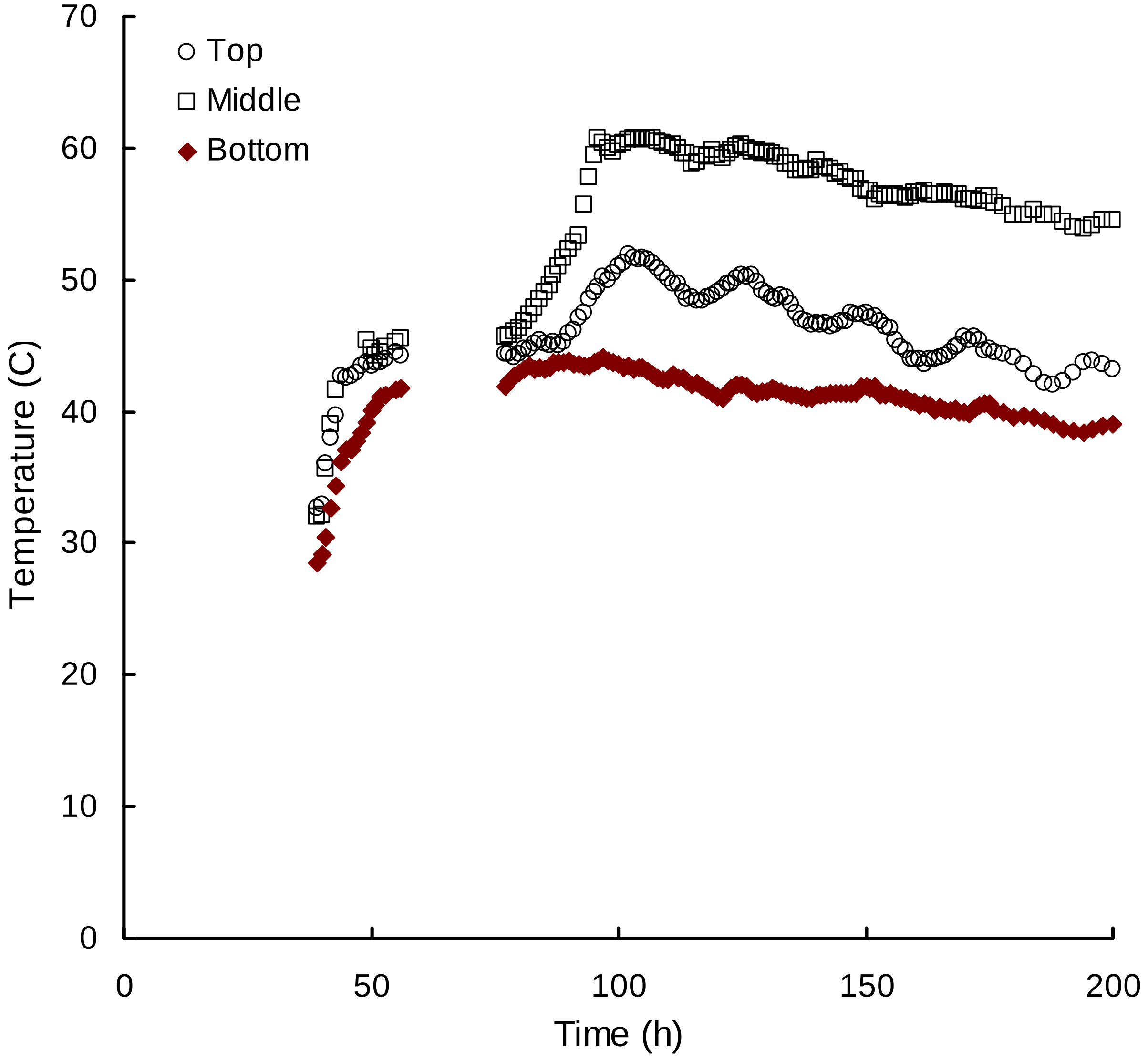
Figure 2. Schematic of the forces on the air in a single compost layer

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

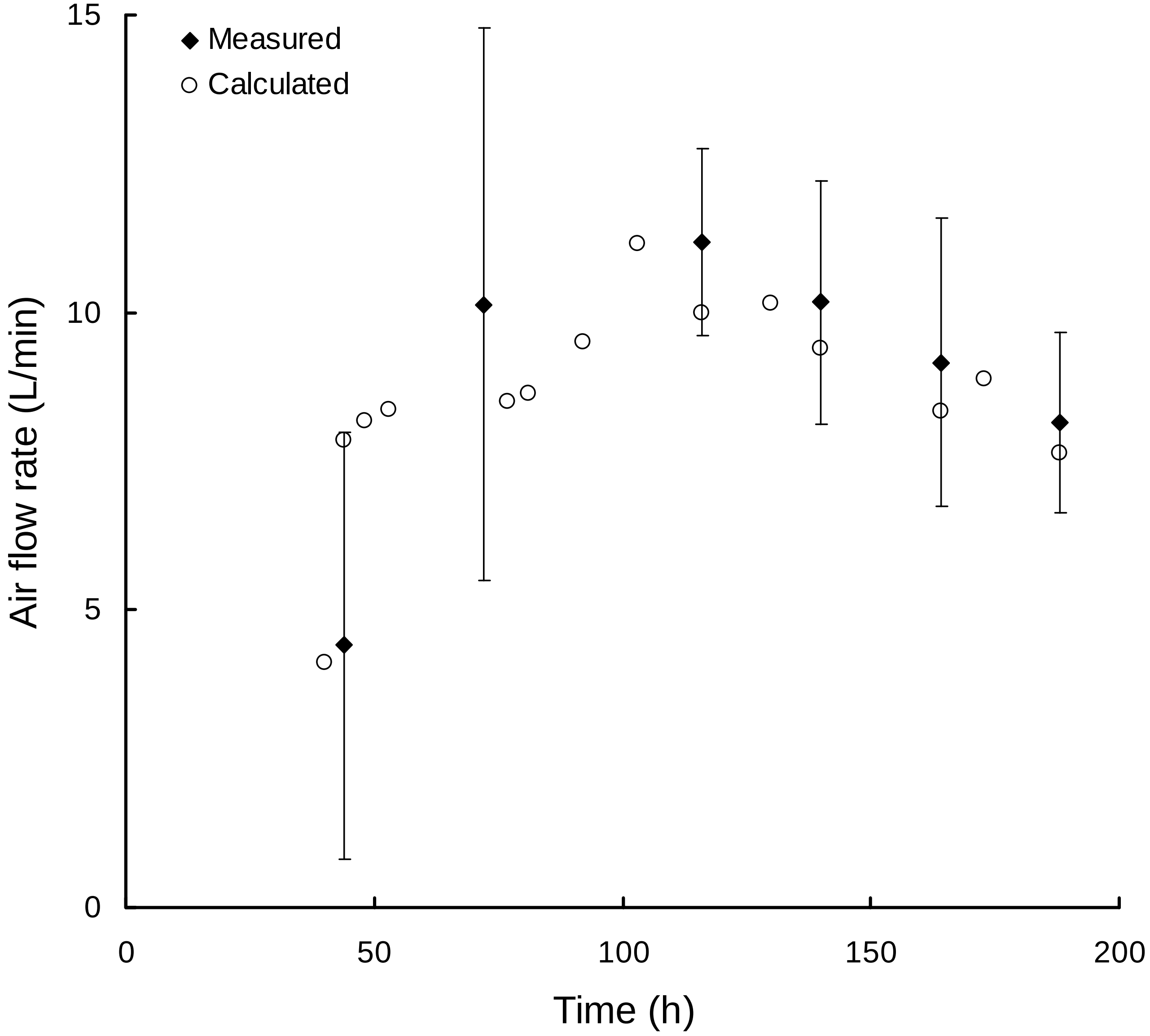
Figure 4. Measured and calculated air flow rates through the compost


Air Outlet
40 mm
Insulated vessel wall
Compost
Top
0.8 m
Middle
Temperature sensors
Bottom
0.1 m
Air Inlet
0.6 m
25 mm


$F_{buoyancy}$
Layer in compost
G



○ Top
□ Middle
◆ Bottom
Temperature (C)
0
10
20
30
40
50
60
70
Time (h)
0
50
100
150
200


15
10
5
0
0
50
100
150
200
Air flow rate (L/min)
Time (h)
◆ Measured
○ Calculated