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EFFECT OF AERATION PATHWAYS ON SPATIAL HOMOGENEITY
DURING IN-VEssel COMPOSTING

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
The Degree Doctor of Philosophy in the Graduate
School of the Ohio State University

by

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*****
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Most of all, I thank God, our omnipresent strength and light in life. I am here today due to God’s guidance and plan, without which there is not any direction or strength to life.
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LIST OF SYMBOLS

\( \varepsilon \)  Porosity of the bed of compost

\( \beta \)  Compressibility coefficient defined by equation 2.4

\( \theta \)  Volumetric water content (m³/m³)
Dimension of time in the numerical model (sec, or hours)

\( \mu \)  Viscosity of fluid (kg/m·sec)

\( \phi_1 \)  Temperature correction for microbial activity, defined by equation 4.22

\( \phi_2 \)  Moisture correction for microbial activity, defined by equation 4.23

\( \rho_{bd} \)  Dry bulk density of compost (kg/m³)

\( \rho_p \)  Particle density of compost media (kg/m³)

\( \Delta P \)  Pressure drop across a bed of porous media (Pa)

\( \rho_w \)  Density of water (kg/m³)

\( A \)  Cross sectional area of compost sample cylinder, or area of element perpendicular to the direction of flow (m²)

\( \text{amb}_O_2 \)  Ambient concentration of oxygen in the air (kg/m³)

\( b_{ca} \)  Mass of air consumed per unit mass of dry matter degraded (kg/kg)

\( b_{cw} \)  Mass of water generated by microbial degradation of dry matter (kg/kg)

\( C \)  Parameter estimated in the Kozeny-Carman equation 2.19

\( C_{O_2} \)  Concentration of oxygen at any spatial location in the compost bed (kg(O₂)/m³(Air))

\( C_p \)  Specific heat capacity of the compost (J/kg·°C)
\( d_{ave} \)  Mean particle diameter of the compost media, Eq 4.45, (m)

\( D_h \)  Hydraulic diameter of the particle, defined by equation 2.13

\( \text{evap}_\text{air} \)  Enthalpy of air at the defined temperature (J/kg)

\( F(t), a(t) \)  Parameters used in the solution of the first order differential equation, in eq 4.42

\( F, Y \)  Parameters of the Spink equation (Eq. 4.1) discussed in Appendix A

\( \text{FAS} \)  Free air space (air filled porosity) of compost media (m³/m³)

\( f_p \)  Particle friction factor, equation 2.20

\( g_{o2} \)  Mass of oxygen consumed per unit mass of dry matter degraded (kg/kg)

\( H \)  Height of bed of compost

\( H_a \)  Enthalpy of air flowing into the compost bed (J/kg(dry air))

\( h \)  Non-dimensionalized height of a bed of compost or an element in a bed of compost

\( h_w \)  Enthalpy of water (J/kg(water))

\( h_c \)  Heat of combustion of the compost material (J/kg(dry matter))

\( i,j \)  Indexes of rows and columns used in the numerical model

\( K \)  Permeability of the compost porous media (m² or µm²)

\( k', k_c \)  Thermal conductivity of the compost material defined by eq 4.31 (W/m-K)

\( k \)  Degradation rate of compost under the local conditions of temperature and moisture (day⁻¹, or sec⁻¹)

\( k_{max} \)  Maximum degradation rate achieved under optimum conditions for the microflora (day⁻¹, or sec⁻¹)

\( k_o \)  Particle shape factor based on the Kozeny-Carman model

\( L_e \)  Equivalent length of flow path due to tortuosity (m)
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<td>MC</td>
<td>Moisture content of compost on a wet basis (kg/m³)</td>
</tr>
<tr>
<td>Mₑ</td>
<td>Dry matter of compost (kg)</td>
</tr>
<tr>
<td>Mₑw</td>
<td>Mass of water in the compost (kg)</td>
</tr>
<tr>
<td>Mₑₑ</td>
<td>Equilibrium mass of compost (kg), equation 2.26</td>
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<tr>
<td>Mₒ₂</td>
<td>Mass of oxygen present in the air (kg)</td>
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<tr>
<td>Mₑₑₑ</td>
<td>Oxygen consumption rate as defined by Kaneko and Fujita (1992)</td>
</tr>
<tr>
<td>P</td>
<td>Compressive stress on compost bed (kPa)</td>
</tr>
<tr>
<td>P</td>
<td>Static pressure at any location within the compost bed (Pa)</td>
</tr>
<tr>
<td>pᵥᵥ</td>
<td>Saturated vapor pressure of air at the defined temperature, Eq 4.25, (Pa)</td>
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<td>Q</td>
<td>Volumetric flow of air through the compost bed (m³(air)/kg(compost))</td>
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<tr>
<td>q</td>
<td>Conductive heat flux in the compost bed (J/m²·sec)</td>
</tr>
<tr>
<td>Reₚ</td>
<td>Particle Reynolds number, equation 2.21</td>
</tr>
<tr>
<td>Rh</td>
<td>Relative humidity of the air (fraction, or %)</td>
</tr>
<tr>
<td>T</td>
<td>Temperature of the compost (° C)</td>
</tr>
<tr>
<td>v</td>
<td>Superficial velocity of flow of fluid through porous media (m/sec)</td>
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<tr>
<td>vₚ</td>
<td>bulk velocity of flow through bed of porous media (m/sec)</td>
</tr>
<tr>
<td>Wₛₛ</td>
<td>Humidity ratio of the saturated air entering or leaving the compost (kg/kg)</td>
</tr>
<tr>
<td>wb</td>
<td>Wet basis, presentation of moisture content (kg/kg)</td>
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<td>Mass flow of air into a bed of compost calculated for the orifice plate measurement, defined in equation 4.1 (kg/sec)</td>
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<td>x,y,z</td>
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<td>Y</td>
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CHAPTER I
INTRODUCTION

Composting is a safe and effective way of handling the biodegradable fraction of the waste stream. For cost efficient composting, an environment must be created that provides optimal nutrients, moisture, temperature, aeration, and pH so as to optimize growth rates of the microflora in the process. The composting microflora utilizes the degradable constituents in wastes as an energy source and releases CO$_2$, H$_2$O, NH$_3$ and biological heat as principal products. The end product of composting should be a stable material that can be applied to soil to improve its physical, chemical and biological properties. Large scale composting is intensive in labor, equipment, and energy utilization. In order to optimize the economics of composting, high degradation rates and subsequent high quality end products must be achieved at low costs.

Numerous researchers have studied composting process control parameters such as temperature, moisture content, nutrients (C/N) and pH for optimal treatment of various materials. Pathogen reduction using thermal inactivation requires uniformly high temperatures in the compost for specified periods of time (e.g. 72 hours, T > 55°C for in-vessel systems). To attain the goals of composting at the lowest operating cost requires conditions to be maintained homogeneously within composting reactors for long durations of time.
The presence of non-homogeneous profiles of temperature, moisture and other properties are common during composting. Previous studies on deep bed composting have described the profiles of temperature, moisture and microbial activity (Hoitink and Kuter, 1983; Miller et al., 1989; Das and Keener, 1993; 1994). These profiles are created by (1) non-homogeneous materials forming the bed, (2) compaction in the bed and (3) porosity profiles due to wall effect. To date, no clear quantification of the effects of these profiles on the degradation rates in the reactor, throughput of the system, cost of composting or effects on the composting environment has been made.

Analytical and numerical modeling of the composting system can be a useful tool in analyzing the effects of various operating scenarios on the spatial homogeneity, kinetics and economics of composting. Numerous attempts at modeling composting systems have been performed, both at a macroscopic level (Smith and Eilers, 1980; Nakasaki et al., 1987; Keener et al., 1993a), and at a particle/biofilm level (Hamelers, 1993). All of these attempts however, have assumed uniform properties within the composting bed and therefore have been unable to quantify the effects of non-homogeneity.

Aeration is the most important controlling factor in composting systems. Air flowing through the bed provides oxygen for the microbes and removes CO$_2$ and heat. Aeration and the corresponding airflow pathways control the spatial distribution of degradation rates, temperature and moisture loss. The ability to predict the flow path of air through the bed will be very useful in modeling the spatial and dynamic processes occurring during composting.
The structure of the bed controls the pathways of air moving through the bed. Airflow related properties in the bed of compost vary depending on the type of material, the type of reactor, initial depth of material, and initial moisture content. In this research four objectives were defined: (1) identify from the literature the factors that cause air flow non-uniformity in aerated deep bed systems; (2) quantify the most important relevant factors and their changes during composting of biosolids; (3) develop and utilize a numerical model of the air flow patterns, and other processes in this composting system to quantify the effects of selected operating scenarios; (4) collect data of spatial and temporal changes in compost bed properties in a full scale system, in order to validate the numerical model and provide insight into changes in bed structure.

The general goal was to study the occurrence, and model the causes of spatial non-uniformity in a Paygro type in-vessel composting reactor. The field experimental parts of this research was conducted at the city of Akron’s biosolids composting facility, located at 2677 Riverview Rd., Akron, Ohio 44313. The reactors were 20 ft wide, 10 ft deep and 720 ft long. Aeration was positive pressure, with the compost bed being aerated from a plenum at the bottom of the bed. The material composted was a mixture of de-watered biosolids (primary), bark, sawdust and recycled compost. The typical detention time for high rate composting in the reactors was 21 days, with material being turned at the 7th and 14th day of composting.
CHAPTER II
LITERATURE REVIEW

Air flow in composting beds is the most critical controlling factor during composting. Aeration is used primarily to supply oxygen to the microbes and remove heat and other noxious products of biodegradation. Temperature control is achieved mainly through evaporative cooling and, therefore, aeration directly affects the moisture level in the composting bed. In large, real world systems, profiles of temperature, moisture, degradation and other properties occur due to non-uniform airflow through the bed and loading the materials to uneven densities. The following sections review the literature on (1) the important factors affecting composting and their optimal values, and (2) the occurrence and proposed causes of non-uniformities in composting beds. The causes of non-uniform airflow are identified and described from the literature on flow in packed beds.

OPTIMUM CONDITIONS FOR COMPOSTING

Numerous studies have been performed to identify the optimum conditions for microbial growth in composting systems. The results of some of these studies and the optimum values of temperature, moisture, aeration rate, particle size, depth of bed, oxygen levels and free air space are outlined below.
Moisture Content

Typically a moisture level of 55-65%(wb) must be maintained for good composting. Golueke (1977) points out that from a theoretical point of view, a 100% moisture level is desirable for optimal microbial degradation. This, however, is not done because adequate oxygen cannot be provided to the microflora due to structural reasons. The composting pile physical matrix has to be maintained without causing the undesirable effects of slumping and compaction, hence the moisture level most commonly used is about 60%. Schulze (1961) determined optimal moisture content based on oxygen uptake measurement due to microbial activity to be 60% for mixed refuse. In the same study it was shown that there was no activity at all at 11.2% moisture. In general, moisture levels below 45% result in reduced bacterial activity and levels of 10-15% in the solid matrix of the compost become inhibitive to most bacteria (Golueke, 1977).

Moisture levels indirectly affect microbial activity by affecting the free air space (FAS) in the interstices of the compost mass. The FAS is the flow path of air and it is from the FAS that oxygen diffuses into the compost particle and biolayer. If excess water is present, FAS is reduced and since the diffusion of oxygen is very slow in water relative to air, anaerobic conditions result. In Schulze's (1961) studies reduced activity above a 60% moisture level was attributed to reduction in FAS.

The factor underlying the lower limit for moisture is that most microbial metabolism occurs in solution (liquid phase). The nutrients and oxygen have to go into solution before being taken up by the microbes for their metabolism. If sufficient moisture (> 45%, as described above) is not present, nutrients and oxygen availability to the
microbes are affected and such moisture limited conditions retard composting. Miller et al. (1989) showed that the microbial mobility within the solid substrate structure is restricted at low moisture levels (low matric potentials). This is another cause of lowered degradation rates.

**Temperature**

The typical high temperatures of compost piles are due to heat output caused by microbial metabolism. Active microbial populations generate heat as a byproduct of breakdown of organic matter. As the temperature of the compost increases, a microbial population shift occurs from mesophilic to high temperature thermophilic populations. This often is beneficial as thermophiles are typically the fastest organisms at degrading the substrate and, therefore, heat build up enhances composting. Thermophilic bacteria, however, have a temperature optimum which peaks around 65°C, e.g. Bacillus stearothermophilus, $T_{opt} = 65°C$ (Finstein and Morris, 1975). Therefore the removal of excess heat is critical to successful composting. If temperatures above a critical limit are reached, microbial activity reduces and at higher temperatures the microbial population can completely be destroyed resulting in thermal inactivation.

In the literature, there seem to be two schools of thought. The earlier literature emphasizes the higher temperatures as optimal for thermophilic composting. In recent years, largely due to the efforts of Finstein et al.(1983) and Strom (1985), the optimal temperatures are accepted to be 50-55°C. Kuter et al.(1985) showed that compost piles which had more than 80% of its mass < 55°C had three times as much activity (based on CO₂ evolution) than piles that had 80% of its mass > 55°C. Based on labeled acetate
incorporated into biomass lipid, McKinley and Vestal (1984) showed that higher activity was seen in compost sampled from regions having temperature 25-45°C. Regions where temperature was above 55°C showed very little activity.

As temperatures exceed 55°C, microbial diversity decreases and only the thermotolerant species survive (Sikora and Sowers, 1985; Strom, 1985). At lower temperatures (< 55 °C) both fungi and thermophilic bacteria thrive. The presence of fungi leads to better breakdown of resistant compounds such as lignin (Chang and Hudson, 1967). From these studies it is evident that maintaining a temperature 40 - 55 °C would be ideal for composting.

Aeration Rate and Strategy

Aeration has three purposes: (1) removal of heat through evaporative cooling, (2) supply of oxygen and (3) drying of compost. Early literature emphasized oxygenation of the compost bed as being the main focus of aeration. Suler and Finstein (1977) recommended aeration based on a feedback control to maintain residual oxygen levels > 10%. Additional studies on aeration to provide oxygen is discussed later in the section on interstitial oxygen availability.

Proper aeration is critical to maintain temperatures within the prescribed optimal range described earlier. Since temperature is an important parameter, typically aeration is operated under feedback control based on temperature. Kuter et al. (1985) showed that three times more activity was seen in compost at a higher total airflow of 23.3 kg(dry air)/hr-m³(compost) than at a lower airflow of 4.6 kg(dry air)/hr-m³(compost). This effect was due to the temperature control effect of aeration. Kaneko and Fujita (1992) used the
ratio \( \frac{Q}{M_{rm}} \) of air flow per mass of compost \( Q \) to the maximum oxygen consumption rate \( M_{rm} \) as an indicator of airflow requirements. Based on measured oxygen consumption rates, they showed that the activity of compost was highest when \( \frac{Q}{M_{rm}} > = 0.005 \text{ m}^3 \text{ (air)}/\text{g (oxygen)} \).

With regard to strategy of aeration there has been the use of both positive flow and negative flow aeration. The use of positive aeration is recommended over negative for the following reasons (Finstein, 1980): (1) it induces evaporative cooling in the insulated interior regions of the pile and transfers heat towards the outer regions, and (2) it enhances the convective upward draft created by the existing temperature profile. Positive aeration also eliminates two problems of negative aeration, namely (1) the "hardpan effect" which is a hardening of the bark base of composting piles due to the migration of leachate to the middle and bottom of the pile, and (2) condensate collection in the suction ducts which causes problems of leachate handling and possible damage to ductwork and fans. Water accumulating in the base of the pile reduces airflow and enhances fermentation.

From the above discussion it can be concluded that positive aeration with a temperature control setpoint of 55° C would be optimal. If the setpoint is 55° C, a fraction of the pile will be around 65° C but not over. It is also known (Finstein and Miller, 1985) that nine times more air is necessary to remove heat in composting than to supply oxygen. Temperature-based control, therefore, ensures that oxygen does not become a limiting factor.
Particle Size

Particle size affects oxygen availability in two opposing ways. When particles are large they develop anaerobic cores due to the inability of oxygen to diffuse to the center of the particle. This reduces the overall activity of the mass. Reduction in activity is also due to the lower surface area per unit volume, resulting in lesser active area that the microbes can attack.

Moderately small particles would be ideal as they have a high surface area to volume ratio and hence offer more active surface area. Unfortunately, small particles compact readily and the mass would have reduced porosity due to denser packing. This results in reduced permeability and inability of air to reach the interstices.

From the point of view of FAS and aeration, the ideal particle ranges from 0.1 to 1.0 cm (Haug, 1980). This causes a problem from a diffusional view point. If particle sizes are larger than 0.1 to 0.2 cm, they are too large for oxygen diffusion and will contain anaerobic cores (Golueke, 1977). It is recommended to use particle sizes in the mid range thereby not causing FAS or diffusional limitations (Haug, 1980).

Depth of Pile

The factors affecting the choice of depth of pile are (1) volume of composting, (2) surface area to volume ratio of the bed and (3) permeability considerations. Large piles (large depth) have the advantage of increasing the amount of material that can be processed per unit reactor floor area. A more important consequence of this is the decrease in surface area to volume ratio. The smaller surface area per unit volume reduces loss of heat compared to heat generated. This effect results in beneficial self heating of the
composting mass. Haug (1980) cites a study of windrow composting, in which it was shown that an increase of 0.5 m² cross-sectional area of windrow resulted in 1.2°C increase in pile temperature.

The downside of large depth is the effects of compaction. The larger the depth, the more the compaction in the lower layers. Schulze (1960), while working with composting municipal solid waste, recommends that windrow heights be not more than 6 ft (1.8m). At depths above this the effects of compaction and reduction in FAS becomes significant resulting in the need for more frequent turning. For forced aeration piles composting biosolids, depths around 8-9 ft (2.7m) can be reached without losing temperature control and moisture removal (Walker, 1993). The compactability of the material which defines the bed depth is specific to the type of material and amendments used and therefore recommendations of bed depths can vary in a wide range.

Another pertinent factor is air entering the pile quickly becoming moisture saturated at the local compost temperature. A critical pile height exists above which the air will not remove any heat by evaporative cooling. Hence very deep compost piles (such as silo type reactors) can have a high temperature zone on the top layers that can lead to temperature inactivation and inefficient composting (Finstein and Miller, 1985).

Oxygen Availability

The air flows through the interstices (FAS) of the compost pile. It is from the FAS that the interchange of oxygen from air (gas phase) to water (liquid phase) occurs. As mentioned earlier, the microorganisms live in the liquid phase and acquire their nutrients in the liquid phase. Since diffusion mass transfer is driven by concentration gradients, the
oxygen concentration in the FAS is an indicator of the amount of oxygen available to the microbes.

Suier and Finstein (1977) found that when the aeration was maintained high enough to retain a residual oxygen level >10% (v/v), dry matter loss was high. A marginal increase in dry matter loss was found when the aeration was raised to maintain a residual oxygen level of 18%, but decreased when the residual oxygen level was raised to 35% by the addition of oxygen to the air stream. Finstein et al. (1986) reported similar results concluding that oxygen was not a limiting nutrient when the interstitial oxygen level was maintained >=10%. In another study Finstein and Miller (1985) found that a well oxygenated condition was defined when the oxygen level was maintained at 17%. Harper et al. (1992) showed symptoms of anaerobiosis occurring when the oxygen level was below 10% oxygen levels.

Benedict et al. (1986) in a study comparing three field size static piles found that an aeration rate maintaining an oxygen level >=5% was sufficient. Stentiford et al. (1985) found that using a wide range of oxygen levels was necessary for optimally using feedback control. In their system aeration was triggered if the FAS oxygen level dropped below 5% and stayed on till it reached 12%. They also found that the position in the pile that the probe was placed was critical and that a local oxygen concentration was not representative of the whole pile.

**Free Air Space**

The free air space in the compost pile is the path through which the air flows. It is therefore directly related to the permeability of compost. Additionally, larger FAS is
required so that sufficient amounts of air can enter the compost and diffuse into the biofilm and the solid matrix of compost.

Optimal ranges of FAS are found to be in the range of 28-32% (Jeris and Regan, 1973). They found that the reaeration capability of compost was substantially reduced when the FAS was less than 28%. The use of bulking agents is aimed at increasing the porosity and FAS so that more aerobic conditions prevail uniformly.

TEMPERATURE AND MOISTURE PROFILES IN COMPOSTING SYSTEMS

Preliminary studies conducted at the city of Akron biosolids composting facility (Das and Keener, 1993) indicated non-uniform drying in the composting reactors at Akron. The moisture loss along the walls of the reactor were significantly higher than at the center of the reactor, indicating higher flows of air along the walls. Das and Keener (1993) estimated airflow non-uniformity based on the temperature profile of air exiting the compost and the moisture profile existing after seven days of composting. The flow through the bed was calculated assuming that (1) the temperature of the air leaving the compost bed was equal to the temperature of the compost at the surface of the bed, (2) air was saturated with moisture when leaving the compost bed and (3) all drying occurring in the compost was due to evaporative cooling by air flowing through the bed. It was shown that as much as ten times more air passed through the region along the walls of the reactor than through the center of the reactor.

Temperature profiles suggesting similar results were seen by Hoitink and Kuter (1983) who studied degradation of biosolids in Paygro type reactors. As much as 20-30°C differences in temperature was seen from the top to bottom of the reactor and from
the walls to the center. They found that when maintaining the compost bed at an average temperature of 65 °C, almost 70 % of the bed volume was above 55 °C and at a mean temperature of 54 °C, as much as 54 % of the bed volume was above 55 °C.

FACTORS CONTRIBUTING TO FLOW NON-UNIFORMITY IN PACKED BEDS

From the literature of flow through packed beds and porous media, numerous factors were identified as causes for flow maldistribution. The following is a list of these factors:

1. Filling effect
2. Wall effect
3. Particle size profile
4. Compaction
5. Channeling/Cracks and Aging
6. Temperature profile
7. Moisture profile
8. Inlet air diffuser profile

A more detailed description of the above listed factors and research results from the literature are presented below.

Effects of Filling, Wall and Particle Size Profile

Describing flow maldistribution in packed beds, Szekely and Poveromo (1975) indicated four possible ways in which spatial non-uniform resistance to flow arises. These are 1) The region in the immediate vicinity of the wall has higher porosity than the bulk, 2) non-uniform packing leading to porosity profiles, 3) segregation of particles of different sizes during filling and 4) fluid passing through the bed is introduced in a non-uniform manner.
In a review paper, Lyczkowski (1982) presents figures of random packings of equal and non equal size spheres generated by Visscher and Bolsterli (1972). Both the resulting packings show a characteristic and non-random porosity profile. These packing distributions show the development of many ordered, nearly square, large structures. These indicate that a small group of smaller particles tend to aggregate, effectively acting as a particle of larger size (Lyczkowski, 1982). This behavior is more clearly discernible in the case of non equal sized spheres. This phenomenon, called clumping, is enhanced in composting and other packed beds where the particles have cohesive properties.

The effect of the wall on porosity variations is described by Benenati and Borosilow (1962). They measured variation in void fraction as a function of distance from the wall in a bed of uniform sized spherical lead shots. The variation resembles a classical damped oscillation curve with significant porosity fluctuation to a distance of 4 to 5 ball diameters from the wall. The bed diameter (D) to ball diameter (d) ratio, D/d, was found to be a parameter of this oscillation and less oscillation was seen with increasing D/d ratio. In the case of composting systems the value of D/d is typically very large, however it is dynamically changing. It is therefore conceivable that the ratio of diameters decreases to a point resulting in effects of porosity non-uniformity.

An empirical equation relating average porosity to the porosity near the wall region (0.5 ball diameter from the wall to the wall) presented by Lyczkowski (1982) is shown below as equation 2.1,

\[ \varepsilon = 1 - \frac{(1 - \varepsilon_w)(0.7293 + 0.5239 \times Y)}{1 + Y} \]

Eq. (2.1)
where $Y = \frac{d}{D}$, $\varepsilon$ is the porosity, with subscript "w" indicating wall region, and "ave" indicating the average porosity. Hence if the average porosity was 0.5, and $Y=1 \times 10^{-3}$, then the porosity at the wall would be 0.64. This magnitude of variation in porosity affects the flow regime significantly.

Stanek and Szekely (1972) developed a model of the flow field in packed beds containing spatially non-uniform resistance to flow. The model was used to predict flow velocities and the predictions and experimental verification was reported by Szekely and Poveromo (1975). The model uses the Ergun equation and the Continuity equations as the governing equations to describe flow. Solving these equations with a knowledge of the spatial distribution of porosity and particle diameters describes the flow regime. Their results show streamlines of flow significantly concentrating in regions of higher porosity, indicating higher velocity and flow in these regions. A channel of higher porosity in the bed causes a preferential flow resulting in 70% of the total flow going through this high porosity region, and this magnitude of channeling was found to be almost independent of the total flow rate. The results of Szekely and Poveromo (1975) also showed that when the wall region has higher porosity than the center, the preferential flow along the walls caused a typical velocity profile similar to that estimated in compost beds during preliminary studies in this research (Das and Keener, 1993).

**Effect of Temperature Profiles**

In the discussion in their paper, Stanek and Szekely (1972) describe the sequence of formation of hot spots in packed beds having exothermal reactions. Local variation in
porosity (or particle size) will result in local variations in mass velocity, thereby varying the residence time of flow and the degree of completion of reaction. Exothermic reactions release heat and the spatial non-uniformity in degree of completion of reaction results in temperature profiles. Localized hotter regions further increases the resistance of flow, leading to hot spot formation.

The model of Stanek and Szekely (1972) is extended to include a heat balance (Stanek and Szekely, 1973) and simulations are made where the system is initially at a constant temperature, and suddenly the temperature of gas flowing through is increased at the inlet plane. The hotter gas enters and flows preferentially through the region of higher porosity (wall region). Very quickly the wall region increases in temperature and provides more resistance to flow, this causes a shift of preference of gas flow to the region of lower porosity.

In composting systems, the typically seen hot spots are in the center of the pile. This region is also the region of low porosity due to wall effects and compaction effects. The air preferentially flows around this region, the higher temperature in the core enhances the resistance to flow and temperature continues to increase. Subsequent cooling occurs only when the thermal activity of the microbes has reduced or if excess quantities of air are supplied to cool the bed.

**Channeling**

Channeling is a common phenomenon in composting systems. If frequent turning of the compost pile is not performed large channels form and air short-circuits. This can lead to significant regions of the pile being inactive due to either too high temperatures or
low oxygen levels. Network models have been used to describe channeling in reaction
related flow in limestone cores (Hoefner and Fogler, 1988) and may be a possible tool in
studying channeling occurring in deep beds during composting.

**Moisture Profiles**

The moisture profiles in composting systems vary both spatially and temporally. As airflow is the source of moisture removal, characteristic flow profiles lead to moisture profiles. The importance of moisture in composting systems has been discussed earlier. High moisture can lead to anaerobiosis due to diffusion limitations, and FAS limitations and compaction of the bed. It has been documented that as moisture increases the pressure drop through packed beds increase (Williams and Miller, 1993), resulting in large increases for the cost of aeration. Further work needs to be done to look at the trade offs between kinetics of degradation and economics of aeration.

**Inlet Air Diffuser Effects**

Although not very obvious, it is possible that the air diffuser system can result in uneven pressure drop over the bed length, and this can contribute to flow non-uniformity. It is intuitively obvious that using a large number of evenly spaced nozzles would lead to a more uniform distribution of flow. The plenum is the ideal case of an infinite number of diffuser nozzles. Nevertheless, it is possible that the pressure pattern inside the plenum is not uniform, due to the presence of leaks in the ducts or in the plenum itself, and the spatially uneven resistance to flow provided by the bed. It was shown by Psarianos et al. (1984) that in windrow composting, equal spacing of holes in aeration ducts with the blower at one end of the duct resulted in non-uniform flow along the length of the
An optimization program was developed to space the holes unevenly thereby delivering the same quantity of air throughout the length of the windrow.

COMPACTABILITY AND PERMEABILITY OF COMPOSTS

The bulk density of compost materials is a function of moisture content and the amount of load on the material. As the load on the material increases the bulk volume decreases due to void space compression. The effect of moisture can be both in reducing bulk voidage due to swelling and increasing the pliability of the material causing easier compression. Therefore, when a dry bulk density is reported, it is essential to know at what moisture content the material was sampled.

The porosity of a material is an important property affecting aeration of composting materials. Porosity is calculated indirectly from knowledge of particle density of the components and the bulk density and moisture content of the material. Porosity directly affects air permeability and therefore the airflow resistance of porous materials, and influences the total air availability to the composting mass at any location in the bed. Therefore, it has an effect on degradation rates, temperature of the bed and moisture profiles in the composting bed.

Numerous studies are reported in the literature (e.g. Chen, 1980; Higgins et al, 1982; Cooper and Sumner, 1985; Keener et al., 1993b) relating pressure drop to inlet air velocity and height of the porous material bed. The effect of compaction has been studied but no study has been conducted to relate the effect of moisture content on compaction and airflow resistance of porous materials. A study of airflow resistances of
sludge/amendments was performed by Chen (1980). Various relationships predicting permeability related properties as a function of inlet air velocity, height of bed and compaction on bed were presented. Using a 9" diameter cylinder, pressure drop as a function of height (0-20") was studied. The following relationship was reported with very high correlations for different mix ratios:

\[
\text{pressure drop (inches of } H_2O \text{) = } K \cdot H^j \quad \text{Eq. (2.2)}
\]

Where \( K \) and \( j \) are parameters and \( H \) is the height of the bed of compost. Using an external load on the sample cylinder (8" deep, 9" dia) containing compost, the compressibility characteristics were studied by varying loads from 0-155 lbs (0-2.44 psi). The moisture content of the material was reported as being 64.5 % (wb). The following relation for bulk density was presented:

\[
\text{Bulk density (lbs/ft}^3\text{) = 36.95*exp(0.185*psi)} \quad \text{Eq. (2.3)}
\]

The data presented (Chen, 1980) show an exponential increase in bulk density up to a pressure of 1.7 psi. Above this pressure, water was seen to be expressed from the sample (saturation state) and no change in bulk volume was seen. This observation indicates the presence of a critical load which is a function of moisture content. Chen (1980) also describes the changes of airflow resistance with age of composting and shows data where the resistance decreases with age of compost. However the bulk density and moisture content also decrease and it is not clear if these are the primary reasons for reduced pressure drop.
Pressure drop studies on grains and other biomass materials such as peanut hulls, woodshavings and bark were reported by Shedd (1953) and by Cooper and Sumner (1985). Linear relationships with depth of bed were shown indicating no compaction. The moisture contents of the materials were 13-15 % (Shedd, 1953) and 5.6-13.4 % (Cooper and Sumner, 1985). The low moisture content and the structural properties of the material may have been the reason for the observed incompactability. Keener et al. (1993b) reported a similar lack of compactability in high moisture content compostable materials such as sludge and amendments, and MSW. The reason for this is probably the fact that when materials were stacked in their setup to a height of 2-3 m, sufficient time was not given for settling to occur.

Chen's (1980) data indicate the presence of the critical point (saturation state) beyond which no significant compaction is seen. Below this critical load the bulk density increases exponentially with increasing loads. This suggests a plastic range (defined by moisture content) in which the bulk density changes indicate structural and void rearrangement.

A MODEL OF COMPACTION AND AIR PERMEABILITY OF COMPOST MEDIA

The compost materials are visualized as aggregates of porous media in a packed bed. Figure 1 shows a schematic of a real bed and its equivalent porous media visualization. The following model is based on the principles of porous media structure, soil compaction, and flow through porous media. The main assumptions and features of the model are listed below:

1. A bed of compost porous media is made up of aggregates.
Figure 1. Schematic representation of a bed of compost porous media (a) with aggregates of compostable materials and (b) its porous media conceptualization with solid fractions, water fractions and void fraction.
2. It is considered that each aggregate (bark, biosolids particle or cow manure particle) consists of solid volume, bound water and internal air void volume.

3. The total airfilled void volume in the bed of aggregates can be divided into macro free airspace which is the inter-aggregate voids and micro free airspace which is the intra-aggregate voids.

4. When compressed (within load ranges typically found in composting due to height of bed) the volume reduction is due to inter-aggregate void reduction and not due to aggregate compression.

5. All the moisture in the material is bound within particle aggregates which can be visualized as shown in figure 1. $V_n$ represents the volume of non-compactable particle aggregate. The section defined as macro voids represents only the inter-aggregate void volume.

6. When external compressive stress ($P$) is applied to the bed of aggregates the reduction in volume follows an exponential decay till it reaches a stable value. This is assumed to be the final compressed state. Macro-porosity is defined as the porosity caused by the compressible fraction of the material, thus, as $P \to P_\infty$, Macroporosity $\to 0$ (Where $P_\infty$ is some maximum compressive stress within ranges normally found in compost beds)

7. The resistance to airflow created by the bed of aggregates is dominated by the presence of macro voids and therefore the effect of micro voids can be neglected.

8. Shrinkage of the aggregates occurs during drying resulting in an increase in the fraction of fines.

Assumption 2 is a common form of visualizing porous media (Haug, 1980; Hillel, 1982). A clear distinction between bound water and free water is not made by these authors. This is due to the fact that both cases arise, as in the study of sand which has all its moisture in the free state and in clay aggregates where a majority of the water is bound and a thin film of water is present on the surface of the aggregates (Bohne and Lessing, 1988). In compost porous media, the most common materials under typical moisture regimes have all their water in a bound state.
Experimental measurements showed that materials with the same total FAS but
different moisture levels, consistently had different permeabilities. Theoretically, if total FAS
directly influences permeability, then materials at the same FAS should have identical air
permeabilities. This discrepancy is explained by the fact that each of these materials had
different macro-porosities, and that drying caused increase in microporosity only, therefore not
affecting the permeability. Air flowing through packed beds of high porosity materials takes
the path of least resistance. In non-uniform materials such as bark and biosolids mixtures, it is
the inter-particular voids that form the path of least resistance. This assumption may not be
valid at a highly compressed state, this however is not the range of application of this model.

Evidence for assumption 4 was obtained experimentally by Braunak (1978) (as cited by
Dexter, 1988). Dexter (1988) developed a semi-theoretical model for the compression of beds
of aggregates that is valid for both plastic (clayey) and brittle soils. Experimental evidence of
compression of sample is given and an equation similar to equation 2.8 was used in their
model.

Data suggesting assumption 8 were observed during the experimental procedure and
validity to these are presented in Figures 10 in the results section. As the material is dried the
total FAS increases, however there was not a proportional increase in permeability. The
resistance to airflow was higher in dry uncompacted samples than in wet uncompacted
samples, as the drying causes particle shrinkage and an increase in packing density, which
decreases macro-porosity.

The definition of macro-porosity is arrived at by assumptions 5 and 6. Due to the
nature of biosolids compost, which is a mixture of fibrous and clayey fractions, the bed deforms
by biosolids particles fusing into the voids of bark. This was observed qualitatively during the experiments. Due to the plastic nature of the materials it is reasonable to assume that within the low values of compressive stresses studied no fracture of bark or solids compression occur.

**Compactive Behavior of Compost Porous Media**

In general form compressibility is defined in terms of equation 2.4 (Castellan, 1983).

$$\beta = -\frac{1}{V} \left(\frac{dV}{dP}\right)$$  \hspace{1cm} Eq. (2.4)

If we separate variables, and integrate, the solution to equation 2.4 is,

$$V_i = V_o \exp(-\beta P_i)$$  \hspace{1cm} Eq. (2.5)

If the area of cross-section of the sample is constant during compression the above equation can be written for the one dimensional case as,

$$H_i = H_o \exp(-\beta P_i)$$  \hspace{1cm} Eq. (2.6)

Equation 2.6 in its current form implies that the sample volume is completely compressible, i.e. as $P$ approaches infinite, $H_i$ approaches zero. In compost beds, a maximum compacted state is reached (Figure 7, Results and Discussions), and this maximum compression that the sample can undergo is $H_\infty$. Therefore equation 2.6 is modified to accommodate this and is written in normalized form as

$$\frac{H_i}{H_o} = \frac{H_\infty}{H_o} + (1 - \frac{H_\infty}{H_o})\exp(-\beta P_i)$$  \hspace{1cm} Eq. (2.7)

The variables in equation 2.7 are renamed for convenience using parameters of the compression curve, and the equation for the nondimensionalized height ($h_i = H_i/H_o$) of the sample at any intermediate compressive stress is given as:
\[ h_i = h_\infty + \Delta h_0 \cdot \exp(-\beta P_i) \] **Eq. (2.8)**

In physical terms, \( h_\infty \), \( \Delta h_0 \), and \( \beta \) represents the maximum compressed state, the total compressible fraction at any compressive stress \( P_i \), and the rate of volume reduction (Dexter, 1988) respectively. Based on porous media assumptions, the physical properties of a sample of compost can be computed based on the parameters of the compression curve and preliminary measurements of weight of sample, moisture content and particle density using the following equations (Hillel, 1982):

\[
\rho_{bd} = \frac{\text{Weight of sample}}{H_i A} \quad \text{Eq. (2.9)}
\]

\[
\varepsilon = 1 - \frac{\rho_{bd}}{\rho_p} \quad \text{Eq. (2.10)}
\]

\[
\theta = \frac{MC \cdot \rho_{bd}}{\rho_w} \quad \text{Eq. (2.11)}
\]

where \( \rho_{bd} \) is the dry bulk density of the sample, \( H_i \) is the height of the sample at any corresponding load, \( A \) is the cross sectional area of the sample cylinder, \( \varepsilon \) is the total porosity, \( \rho_p \) the particle density of the sample, \( MC \) the moisture content of the sample and \( \rho_w \) is the density of water. The free air space of the sample is calculated as

\[
\text{FAS} = \varepsilon - \theta \quad \text{Eq. (2.12)}
\]
Permeability of a Bed of Compost Porous Media

For fine homogeneous particle beds the permeability is a function of porosity, shape and orientation of particles, surface area exposed to flowing fluid and the pore size distribution (Dullien, 1992). A large number of studies are cited in his book and Dullien (1992) concludes that there is no universal theoretical relationship between permeability and porosity. The commonly used relationships either depend on the assumption of the type of model describing flow (e.g. the capillary flow model) or are semi-empirical, phenomenological models. In the Kozeny-Carman model the permeability is described as a function of the air porosity (FAS), particle shape factor (\(k_o\)), tortuosity (\(L_e / L\)), and specific surface area (S). In the following section the relationship between the variables in the Kozeny-Carman model of permeability are derived from fundamentals.

The Kozeny-Carman Model of Flow Through Porous Media

The Kozeny-Carman "mean hydraulic diameter" model is conceptually simple and is a widely used model (Dullien, 1992). It assumes that the porous media is a conduit of complex tortuous nature, but has a mean cross-sectional area of flow giving a mean hydraulic diameter defined as,

\[
D_h = \frac{4 \times \text{Void volume of medium}}{\text{Surface area of Channels}}. \quad \text{Eq. (2.13)}
\]

Using a Hagen-Poiseuille type relation the bulk velocity is expressed as,

\[
v_b = \frac{\Delta P}{L_e} \left( \frac{D_h^2}{k_o \mu} \right). \quad \text{Eq. (2.14)}
\]
Normally, by the Dupuit-Forchheimer's assumption the bulk velocity is written as the superficial velocity divided by the air filled porosity, Carman introduced the correction for tortuosity of path by multiplying by \((L_e/L)\) and this results in the bulk velocity expressed as:

\[
V_b = \frac{V}{\varepsilon} \left(\frac{L_e}{L}\right).
\]

Combining Equations 2.14 and 2.15 with the Darcy's law as shown in Equation 2.16, the permeability of the porous medium can be written as equation 2.17,

\[
\nu = \frac{K}{\mu} \left(\frac{\Delta P}{L}\right).
\]

\[
K = \frac{\varepsilon D_h^2}{16k_o \left(\frac{L_e}{L}\right)^2}.
\]

The hydraulic diameter for a bed of spherical particles by the definition in Equation 2.13 is

\[
D_h = \frac{4\varepsilon}{S_o (1 - \varepsilon)}.
\]

Substituting 2.18 into 2.17 gives equation 2.19, the standard form of the Kozeny-Carman equation,

\[
K = \frac{\varepsilon^3}{k_o \left(\frac{L_e}{L}\right)^2 S_o^2 (1 - \varepsilon)^2}.
\]

In the denominator \((L_e/L)^2\) is the tortuosity factor, \(k_o\) is a particle shape factor, \(S_o\) is the specific surface area of the particles and the product \((1/k_o(L_e/L)^2S_o^2)\) is commonly called the Kozeny constant (C).
An alternate empirical way of reaching equation 2.19 (Dullien, 1992) is from the definitions of the friction factor (equation 2.20) and particle Reynolds number (equation 2.21),

\[ f_p = \frac{D_p \Delta P}{\rho \nu^2 L} \quad \text{Eq. (2.20)} \]

\[ \text{Re}_p = \frac{D_p \nu \rho}{\mu} \quad \text{Eq. (2.21)} \]

If we take the product of \( \text{Re}_p f_p \) from equations 2.20, 2.21 and introduce the Darcy's law from equation 2.16 we get,

\[ f_p \text{Re}_p = \frac{D_p^2}{K} \quad \text{Eq. (2.22)} \]

Equation 2.22 is of a general form of friction factor = Constant/Reynolds number, as in laminar flow cases. This implies that Darcy's law is applied with permeability \( K = D_p^2/\text{Constant} \).

Numerous correlations of \( \text{Re}_p f_p \) as a function of \( \varepsilon \), to determine a porosity function is found in the literature. Further details can be obtained from Dullien (1992), page 242, Table 3.1 The special case of the Kozeny-Carman equation comes from the choice of the porosity function as

\[ f(\varepsilon) = \frac{\varepsilon^3}{(1 - \varepsilon)^2} \quad \text{Eq. (2.23)} \]

**MATHEMATICAL MODELING OF THE COMPOSTING ECOSYSTEM**

Mathematical modeling of an ecosystem helps understand the dynamic relationship between the various state variables that describe a system. Successful system models can accurately describe behavior of the system under different scenarios, and therefore design and
management insight can be obtained without expensive investment of time, effort and money. In the area of composting, several attempts at modeling of the system have been made. Both analytical modeling (Nakasaki et al., 1985; Keener et al., 1993a; Hamelers, 1993; Haug, 1993; Lynch and Cherry, 1995), and numerical modeling (Smith and Eilers, 1980; Stombaugh and Nokes, 1994) approaches have been attempted. The following review highlights some of the major features, and limitations of these models of the composting system, and outlines the two dimensional finite difference model currently implemented in this dissertation.

Smith and Eilers (1980) implemented a two dimensional finite difference model of forced aerated windrow composting of biosolids. They covered spatial and temporal solutions of air flows, substrate degradation, and heat, water, and oxygen balances. In their model they assumed that the flow patterns and quantities of air were independent of time. It was necessary to solve the flow equations spatially as the geometry of the windrow was not uniform and the boundary conditions were not all the same. However, the assumption of constant permeability throughout the bed, and temporally constant air flow pattern causes the model to be insufficient in studying the rapidly changing spatial and temporal variations in properties during high rate composting. The model accounts for spatial and temporal changes in dry matter and therefore microbial degradation rates. The field validation of the model proved that the dry matter, volatile matter and moisture content were accurately predicted, however temperature predications were not close in two of their four runs. The data presented from their simulations and validations did not attempt to compare spatial predications.

A model describing kinetics based on $R_{\text{CO}_2}$, the CO$_2$ evolution rate was reported by Nakasaki et al. (1987). $\text{CO}_2$ evolution rate as a function of temperature of the compost, and
volatile matter conversion percentage was measured in the laboratory and used as the driving input to the model. The simulation was started assuming a value of $R_{\text{CO}_2} = 1 \times 10^7$ mole (CO$_2$)/g(dry solid)-hr, temperature as ambient and volatile matter conversion rate as 0%. Using these initial conditions and the relationship between these variables the values of temperature, and volatile matter conversion rate for the next time step was calculated from mass balances and knowledge of a conversion factor, $g$(organic matter degraded)/mole (CO$_2$ evolved). The model is a single cell numerical model and does not account for spatial variations. A constant aeration of $4.97 \times 10^3$ m$^3$/kg (initial dry matter)-hr was used in their simulation, the results of temperature, dry matter loss and moisture loss were reasonably accurate compared to a validation run.

A particle level mathematical model of composting kinetics based on fundamentals of biofilm theory was presented by Hamelers (1993). The model describes the system using polymeric substrate, monomeric substrate, microbial biomass, oxygen and water concentrations as the state variables. Reaction rates describing conversion of substrate, and biomass growth are modeled after first order kinetics and Michaelis Menten type multiple substrate dependent rates. The dynamic solution of the equations were performed using numerical methods. No description of the domain of computation other than particle level is described in the paper. The model is validated only for the oxygen uptake rate (OUR) of the compost material using a 0.07 m diameter, 0.3 m long cylinder as the reactor.

A detailed description of modeling of composting as a continuous feed complete mix reactor is presented by Haug (1993). Multiple substrates are usable and substrate degradation is modeled using first order kinetics. Heat, moisture, substrate, and gas balances (Water vapor,
O₂, CO₂, and NH₃) are described in detail. Dynamic simulations are performed and the relationship between variables are described. The multi-stage model can be used to calculate spatial profiles within a bed, but this implementation is not done explicitly.

A one dimensional finite difference model of the composting system was presented by Stombaugh and Nokes (1994) in the context of using it as a teaching aid in a bioprocess engineering course. The model was validated by comparisons with a laboratory composter composting a mixture of cracked corn and pelletized corn cobs. The model is based on modeling microbial biomass growth using Monod growth kinetics. Substrate degradation rates are established using conversion factors based on stoichiometry of degradation and parametrization for reasonable values. A detailed sensitivity analysis of the various parameters is made and an evaluation of the cost of composting as a function of reactor depth is performed.

Lynch and Cherry (1995) developed equations from fundamentals to describe air flow in passively aerated windrows. Their model is based on free convection flow and describes anticipated air velocity profile along the length of the windrow. Some simplifying assumptions are made such as, temperature and air permeability of the bed is uniform, and no loss in mass of air occurs due to microbial respiration. The model does not describe the other phenomena in composting such as, degradation of dry matter, temperature increases, oxygen consumption, CO₂ evolution and moisture loss. The results of their model are useful in understanding the effect of placement of aeration pipes in the bed of a passively aerated windrow, and the effect of differences in porosity between the compost media and the porous bed media used in passively aerated windrows. Very large differences between permeability of compost bed
media and that of the bed media resulted in significant reduction in airflow at points between aeration pipes. This occurrence leads to heat build up in these regions and can result in anaerobic conditions.

An analytical model describing all the macroscopic phenomenon occurring during composting was developed by Keener et al. (1993a). The concept of equilibrium mass, indicating the fraction undecomposed after a long period of time, is introduced and a mass ratio is defined. In their paper, Keener et al. (1993a) have assembled a data base of properties of various compostable substrates and presented design procedures and constraints such as, fan sizing for aeration, variable and fixed costs, effect of depth of compost on cost, etc. Procedures outlining optimization of parameters are presented along with calculations for special cases with comparisons.

**A Two Dimensional Finite Difference Model of the Composting System**

In this dissertation a numerical model is implemented to quantify the effects of spatial non-uniformities in full scale in-vessel reactors. The model focuses on air flow pathways as the controlling factor of other processes in composting. A two dimensional domain is defined, representing the reactor, and the velocity profile of air is calculated by the simultaneous solution of Darcy's equation and the Continuity equation. Heat, mass, oxygen, and carbon dioxide balances are performed similar to the model presented by Keener et al. (1993a). These equations are described below.

The governing equations used for calculating air flow are the Continuity equation,

\[
\frac{\partial (\rho \varepsilon)}{\partial \theta} = \frac{\partial (\rho V_x)}{\partial x} + \frac{\partial (\rho V_y)}{\partial y} + \frac{b_a}{D} \frac{dM_s}{d\theta} \quad \text{Eq. (2.24)}
\]
and the momentum balance in the form of Darcy's equations,

\[ V_x = \frac{K}{\mu} \frac{\partial p}{\partial x} \quad \text{and} \quad V_y = \frac{K}{\mu} \frac{\partial p}{\partial y} \quad \text{Eq. (2.25)} \]

Where, \( V_x \) and \( V_y \) are the air velocity components, \( K \) is the permeability and \( \mu \) and \( \rho \) are the viscosity and density of dry air at the local temperature. The airfilled porosity is given by \( \varepsilon \), the mass conversion of air due to oxygen consumption is given as \( b_{oa} \), \( P \) is the hydrostatic pressure at each location, and \( dx, dy, dz \) are the dimensions of individual cells. \( M_e \) is the dry matter of compost, and \( \theta \) is the variable representing time coordinates.

The two equations (2.24 and 2.25) are combined and solved iteratively for the pressure at all spatial locations. The values of all other parameters are explicitly known at each spatial location. The calculated pressure profile is used back in the Darcy's equation to determine the velocity vectors.

The degradation of dry matter is modeled after the first order kinetics equation presented by Keener et al. (1993a), which is

\[ \frac{dM_e}{d\theta} = -k (M_e - M_e^*) \quad \text{Eq. (2.26)} \]

where \( M_e \) is the mass of dry matter at any spatial location and \( M_e^* \) is the equilibrium dry matter evaluated as \( M_e^* = \beta M_c \) (at time \( = 0 \)). This factor is the non-decomposable part of the compost mix and \( k \) is the degradation rate constant which is a function of temperature and moisture levels.

The moisture transport phenomena modeled are (1) evaporative removal of water by air and (2) generation of water by microbial action. The following equation was used,
Where, $W_{st}$ is the absolute humidity of saturate air at the local temperature, $M_{cw}$ is the mass of water in the compost, $M_*$ is the mass flow of air into and out of the cell, $b_{cw}$ is the metabolic output of water, i.e. the amount of water produced per unit mass of dry matter degraded.

The phenomena modeled in heat transport are (1) sensible heating of air, (2) evaporative cooling by air and (3) conductive transport. The conductive flux into any cell is defined for example in the $X$ direction as,

$$q_x = k_c \frac{\Delta T}{\Delta X}$$  \hspace{1cm} \text{Eq. (2.28)}$$

$q_x$ is the conductive heat flux, $A$ is the cross sectional area of heat flow, $\Delta T$ is the temperature gradient across a spatial distance $\Delta X$, $k_c$ is the thermal conductivity of compost that is a function of the moisture content of the compost. The temperature at each spatial location is calculated by solving the overall heat balance presented below,

$$M_c C_p \frac{dT}{d\theta} = -h_e \frac{dM_e}{d\theta} - (H_{s,in} - H_{w}(W_{s,in} - W_{s, out} ) - H_{s, out}) M_* + \left[\left(\frac{q_x}{A}\right)_{in-out} + \left(\frac{q_y}{A}\right)_{in-out}\right]$$  \hspace{1cm} \text{Eq. (2.29)}$$

in the above equation $T$ refers to the temperature of compost in °C, $H_s$ is the enthalpy of moist air, $H_w$ is the enthalpy of water at the specific temperature, and $h_e$ is the heat of combustion of the compost material.
The concentration of oxygen is calculated by a mass balance around each computational cell. The following equation describes this balance:

$$\frac{d(M_{O_2})}{d\theta} = C_{O_2, in} AV_{in} \epsilon - C_{O_2, out} AV_{out} \epsilon + g_2 * \frac{dM_e}{d\theta}$$  \hspace{1cm} \text{Eq. (2.30)}$$

$M_{O_2}$ is the mass of oxygen, $C_{O_2}$ is the concentration, and $V$ represents velocity of air flow. The coefficient $g_{O_2}$ is the consumption rate of oxygen (defined as negative). The coefficient values are calculated from the stoichiometry of degradation (Keener et al., 1993a).

**SPATIO-TEMPORAL VARIATION OF PROPERTIES IN DEEP BED COMPOSTING**

Airflow affects both physical and chemical changes during composting. Non-uniform airflow patterns lead to conditions such as spatially non-uniform rates of degradation, rates of drying, rates of cooling etc. Almost every paper where spatial measurements are made in composting has mentioned the presence of large variations within the windrow or reactor. However, only a few attempts have been reported where systematic evaluation of these profiles have been made in order to quantify its effects or identify its causes. Important properties that affect kinetics of degradation and airflow would be (1) temperature, (2) moisture contents, (3) bulk density (4) volatile matter and (5) particle size distribution or mean particle diameters.

Miller et al. (1989) obtained oxygen and temperature profiles in a 2.2 m wide, 1.8 m high bed of naturally ventilated mushroom compost. In their studies it was concluded that airfilled porosity of the bed was one of the main factors affecting the diffusion of
oxygen into the matrix of the compost. Low values of porosity caused poor diffusion, leading to anaerobic conditions. Porosity of the bed also affects fan power requirements and the pathways of airflow through the bed. They found that rates of natural air convection, diffusion of oxygen, and utilization of oxygen varied spatially. The variations were documented spatially and temporally and numerous profiles are presented.

A study of changing structural properties of a refuse composting curing pile over long periods of time was reported by Tietjen and Banse (1961). They determined vertical profiles of moisture, dry solids and porosity in a 1.7 m deep curing pile. The samples were obtained by using a 1000 cc "Burger cylinder" inserted into the compost using a tripod sample cylinder inserting mechanism. Results of their study indicated that airfilled porosity was lowest at the bottom of the bed and highest at 0.7 to 0.9 m depth. The condensation of moisture at the top of the bed caused airfilled porosities to be lower than at the middle of the bed. Moisture and dry matter distributions clearly indicate the presence of a surface condensation zone and a bottom anaerobic zone of lower degradation rates. The region of highest degradation was found to be in the core of the bed.

Mears et al. (1975) presented data on changes in compost properties with time during the composting of a mixture of swine wastes, and straw (10% v/v). They looked at numerous factors such as thermal properties, particle diameter, compressibility and bulk density changes with age of compost. No attempt to look at spatial changes were made in their study. Particle size distribution was measured using the ASAE Standard S 319 (ASAE, 1970). They found that average particle diameter reduced significantly during
composting from a starting value of 2.25 cm to less than 0.2 cm after 4 weeks of composting in windrows that were turned daily. Two windrows that were turned less frequently and did not use sufficient bulking agent in the starting mix were found to have lesser reductions and the mean particle diameter was 1.8 cm even at the end of 10 weeks of composting.

As part of a base line evaluation of composting biosolids in Paygro type reactors, Hoitink and Kuter (1983) performed extensive and detailed studies on the material balances, temperature and aeration effects, and CO₂ evolution in these systems. Their report is a useful guide to the expected performance of these reactors, outlining optimal aeration requirements, temperature and moisture loss regime, and kinetics based on CO₂ evolution. During their summer trial, after 18 days of composting the moisture at the surface of the bed was found to be significantly (0.05 level) higher than at the rest of the bed. No difference was found across the horizontal cross section of the bed. In the same run, the volatile solids remaining were found to be highest at the surface of the bed, and this was significantly different from the rest of the bed region. During the winter trials the volatile solids remaining were found to be lowest at the bottom 1.0 m of the bed, and this was significantly different from the rest of the bed.

The temperature profile (Hoitink and Kuter, 1983) collected for the summer runs showed that when high aeration was provided to maintain mean temperature at 42 °C, almost 30 % of the reactor was in the range of 50 - 60 °C, and the remaining was in the range of 30 to 45 °C. In the case of low aeration, so as to maintain a mean temperature of 65 °C, a range of measured temperature of 30 - 70 °C was found in the reactor. Almost
50 % of the reactor was 30 - 60 °C, and the remainder was above 60 °C. Hoitink and Kuter (1983) suggest that in order to attain efficient pathogen reduction and conform to EPA regulation, the system should be operated with positive aeration for the first part of composting, followed by reversing aeration to negative pressure during the later stages of composting. This would ensure that 100 % of the reactor has achieved and maintained high temperatures required for pathogen reduction. More frequent turning of the compost bed would be another more expensive alternative.

The focus of future designs of systems should be to minimize variations in operating conditions within the reactor. Completely mixed reactors are the ideal case, and many systems (e.g. IPS) operate on a daily mixing principle. The results of the above studies and further studies in spatial non-uniformities have to be analyzed to determine the effects of these non-uniform conditions on the total cost of composting. Numerical modeling and simulation of the systems and various operations (e.g. turning, aeration strategy, moisture readdition etc.) related to composting will be the topic of study in this dissertation research.
CHAPTER III
OBJECTIVES

The overall objective of this research is to study properties affecting airflow during deep bed composting, and to numerically model the effects of air flow pathways on the spatial homogeneity, kinetics and economics of composting.

The following specific objectives are identified:

1. To measure the compactability of biosolids compost as a function of the initial moisture content of the material.
2. To quantify the reduction in air permeability of biosolids compost due to compaction.
3. To implement a two dimensional dynamic numerical simulation model of the composting system that includes, air flow pathways, kinetics of degradation, and heat, water, \( \text{O}_2 \), and \( \text{CO}_2 \) balances.
4. To conduct a field study of spatial and temporal changes in selected physical properties of biosolids compost materials. This study will be used to validate the working of the model developed in objective 3.
CHAPTER IV
MATERIALS AND METHODS

COMPACTABILITY AND PERMEABILITY OF COMPOSTS

In this stage of the research, the compactability and air permeability changes of two composts, namely, biosolids and cow manure compost were measured in the laboratory. Biosolids compost was sampled from the reactors at the city of Akron composting facility during the first 2-3 days of composting and brought into the laboratory at Wooster. Cow manure samples were collected from the Dairy Science Research Center of the OARDC, Wooster. The following is a description of the sampling, sample preparation and experimental procedure during the experiment.

Figure 2 shows a schematic of the experimental setup. The sample cylinder used was 0.30 m (12 in.) in diameter. The sample compost was filled to a depth of 0.41 m (16 in.). Air was forced in through a 2" SCH 40 pipe, id 0.0525 m (2.067 in.). The volumetric flow into the sample cylinder was measured using an orifice plate. The pressure drop across the orifice plate was measured using a 0-1 inch H$_2$O incline tube manometer and equation 4.1 (Spink, 1967) was used to calculate the mass flow

$$W_h = 359S D^2 F_k F_m F_c Y (\gamma h_s)^{1/2}$$  Eq (4.1)

The above equation is written in English units. A description of the values of coefficients in the Spink Equation and a sample calculation are presented in Appendix A. Further information
Figure 2. Schematic drawing of the setup used for compactability testing of biosolids and cow manure compost materials. All numbers indicated are distances in meters.
can be obtained from Spink (1967). Control valves were used to control flow into the sample cylinder. A bleed valve was provided to ensure safety while controlling flow to obtain low velocities. A perforated retainer plate and a force distribution plate were placed on top of the sample. This held the sample and helped distribute the mechanical load evenly over the sample cylinder cross-section. The whole setup was placed in a model 37F hydraulic press (Mfg. K.R. Wilson, Buffalo, NY)

Sampling Procedure and Sample Preparation

Biosolids compost samples were obtained from the in-vessel reactors at the City of Akron Compost Facility. The material was a three day composted mixture of biosolids:recycle:bark:sawdust = 0.34:0.45:0.18:0.03(v/v). The moisture content of the material at sampling was 57.4 %(wb). The material was transported to the laboratory at the Agricultural Engineering building OARDC, Wooster, Ohio where the testing was performed. The cow manure samples were collected from the Dairy science research center of the OARDC, Wooster. The material was a mixture of dewatered cow manure and bedding. The two compostable materials were prepared identically for testing, with the exception that the moisture levels of the cow manure was higher than that of the biosolids in all cases.

The materials were separated into four fractions in the laboratory. The first fraction was used directly in the study. The remaining three fractions were sun dried with periodic stirring on a clean concrete floor for durations ranging from 2 to 6 hours. At two hour time intervals each fraction was taken into the laboratory for study. Each test fraction was first
mixed well and subsamples were taken for moisture content evaluation. All measurements were done on three independently selected random samples of the material.

**Particle Density Measurement**

The particle density of the compost mixes were measured on the wettest fraction following the Pycnometer method described by Blake and Hartage (1986). About 1000 g of compost sample was separated and its moisture content was evaluated by oven drying representative samples at 105 °C for 24 hours. A clean 100 mL flask was weighed empty ($W_s$), and approximately 50 g of compost was added to it. The weight of the flask with compost was measured as $W_t$. Previously boiled and cooled water was added to the flask with compost, the material was slightly stirred to release any air bubbles. When the flask was full of water at room temperature, the weight of the flask, compost and water was measured ($W_{sw}$). The flask was emptied, cleaned and the weight of the flask with only water was measured ($W_w$). The following equation was used to calculate the particle density ($\rho_p$, kg/m$^3$)

$$\rho_p = \rho_w \frac{W_t - W_s}{(W_t - W_s) - (W_{sw} - W_w)}$$

Eq (4.2)

where $\rho_w$ was the density of water equal to 1000 kg/m$^3$.

**Compaction-Pressure Drop Test Procedure**

In each run, a known weight of material was filled into the sample cylinder to a depth of 0.4 m. Care was taken to ensure that the material was well mixed prior to filling and no compaction of the sample occurred during filling. The perforated retainer plate and the force distribution plate (see Figure 2) were placed on the sample. The initial depth of the sample was
recorded and the pressure drop was measured at five superficial velocities in the range of 0.05 - 0.20 m/sec. The pressure drop was measured from the bottom of the plenum to atmospheric pressure using a 0-4 inch H2O inclined tube manometer.

After one scan the material was compressed using the ram of the hydraulic cylinder to an effective compressive stress of 6.97 kPa. While this stress was maintained on the sample, the height of the sample was measured and the pressure drop was measured at the five superficial velocities as before. The compressive stress was raised to levels of 13.9 and 20.8 kPa and the process was repeated. Finally the compressive stress was raised to 43.2 kPa and the compression of the sample was recorded. At this compression pressure drops over 12 inches/ft was reached. This description entailed one replication of one run. Each run (one moisture level) was replicated three times. Four runs were performed at different moisture levels. In the case of cow manure samples the maximum compressive stress was 20.76 kPa.

NUMERICAL MODEL OF COMPOSTING

The numerical model of composting focusses on air flow through the porous compost media. The solution of the Darcy's laminar flow equation simultaneously with the Continuity equation serves to define explicitly the velocity vectors of air flow in the spatial domain. The model was written so as to account for changing physical properties of the porous media and the air, hence the pressure profile was solved for independently at each time step. Changes resulting from bed degradation and drying were not incorporated at the present time due to a lack of existing data for these relationships. It is conceived that these additions will be made at a future point. Following the solution of air flow,
degradation of substrate, heat, water and oxygen balances were performed. The description of the domain of computation, development and implementations of the equations, solution techniques, and calculation errors are described here.

Layout of Composting Reactor And Computations

Figure 3 shows a schematic of the reactor and its computational domain representation. The reactor is 6.1 m (20 ft) wide and was typically filled to a depth of 3.0 m (10 ft). The whole reactor domain, excluding boundaries was stored in an array of size “i_max” rows, and “j_max” columns. Where, i_max and j_max were variables set at 20, and 11 in the program. Several sizes of computational cells were tested before deciding on this size which provides both speed of computation and a low resulting computational error.

Computational Procedure of Model

Computation begins by evaluating the effect of compaction and the resulting profiles in bulk density, porosity and permeability in the bed. Next the mass of water, dry matter, and equilibrium mass in each cell is calculated. Thereafter, initialization of the computational arrays for oxygen concentration, oxygen mass and temperature are made. Finally the dynamic calculations of air flow, degradation, moisture movement, temperature, and oxygen concentrations in the bed is performed for each time step. The dimensions of the computational cell is defined as dx in the X-direction and dy in the Y-direction, where dx = width of reactor/j_max, and dy=height of material filled/i_max.
Figure 3. Schematic of the computational domain of the compost model. The model uses the finite difference scheme of computation and the corresponding grid is made of rectangular cells. Cells are indicated by i, j representing rows and columns.
Fan Control by Temperature Feedback

A subroutine was written to simulate the temperature feedback control used for aeration control in composting. Since air flow is controlled by fan power as the boundary condition, fan power was reset based on the temperature of the bed. A location in the bed equidistant from the walls (i=15, j=6), and in the surface region of the bed was chosen as the point of temperature sensing for fan control. At each time step the temperature of this location was checked and the following control was performed,

\[
\text{if}(\text{temperature} < 50.0^\circ \text{C}), \text{fan\_power} = \text{fan1} \\
\text{else if}(\text{temperature} < 65.0^\circ \text{C}), \text{fan\_power} = \text{fan2} \quad \text{Eq. (4.3)} \\
\text{else} \quad \text{fan\_power} = \text{fan3}
\]

The three fan settings were maintained as global variables at the header of the program for easy changes, the values used were changed depending on the permeability of the media. A representative set of values were \text{fan}1 = 0.5, \text{fan}2 = 1.0 and \text{fan}3 = 2.0 W, where fan power values are for a one meter slice of the compost reactor. The subroutine was written such that a switch from one fan level to another occurs only if both the temperature changes and the fan in its present condition has run for at least 2 hours. This was done to prevent the occurrence of oscillations around a temperature value occurring at each time step. The lag duration of 2 hours was chosen for most simulations. This lag can be easily changed to satisfy any other interval.
Calculation of Profiles Due to Initial Compaction of Bed

The compaction equation used to calculate bulk density and porosity profiles was that developed for a specific compost mix of biosolids-bark-sawdust-recycle. The compression parameters $h_o$, $\Delta h_o$, and $\beta$ are related to the moisture level by linear regression equations as follows:

$$\Delta h_o = 0.004 + 0.007 \times MC$$

$$\beta = -0.017 + 0.002 \times MC$$

$$h_o = 1 - \Delta h_o$$

Additional description of these parameters and the development of these equations are presented in the section on compactability of compost mixes in this dissertation. The relationship between porosity and permeability in the bed of compost is given by the Kozeny-Carman equation (Eq. 2.19) where the Kozeny constant ($C$) is a function of moisture level and was found to be:

$$C = 1286.07 \times MC - 47458.06,$$  \hspace{1cm} \text{Eq. (4.5)}

For the range 43 to 58 %, $wb$, $R^2 = 0.96$.

Computation begins by setting the elements in the top row ($i_{\text{max}}$) as uncompressed, due to no load acting on it. All elements in other rows are compressed due to the load caused by the material above it. Each cell $(j)$ in row "i" was considered to have a compressed height $dy$, and an uncompressed height "init$_{\text{dy}}$". The load on the $j^{th}$ element in the $i^{th}$ row and its uncompressed height are given as,

$$\text{load}(i,j) = \text{load}(i+1,j) + [\text{init$_{\text{dy}}$}(i+1,j) \times \text{initbulk} \times 0.00981] \text{ kPa}$$  \hspace{1cm} \text{Eq. (4.6)}
init dy(i,j) = \frac{dy}{h_0 + \Delta h_0 \exp(-\beta * load(i,j))} \quad \text{Eq. (4.7)}

where init bulkd is the initial uncompressed wet bulk density of the material. The above two equations are repeatedly applied to the entire length of the profile. The increase in bulk density and decrease in porosity due to compression is calculated for the profile using the following equations,

\begin{align*}
\text{bulk } d(i,j) &= \frac{\text{init } dy(i,j) \text{*init } bulkd}{dy} \quad \text{Eq. (4.8)} \\
\text{porosity}(i,j) &= 1 - [(1 - MC) \frac{\text{bulk}(i,j)}{\rho_p} - [MC \frac{\text{bulk}(i,j)}{\rho_w}]] \quad \text{Eq. (4.9)}
\end{align*}

where MC is the initial moisture content of the material, \(\rho_p\) and \(\rho_w\) are the particle density of the material and the density of water respectively. The initial uncompressed porosity is calculated using equation 4.9, but with "bulk[i]" replaced by the value for uncompressed bulk density, "init bulkd". In this model the term porosity represents the air filled porosity. The permeability of the material is computed using the Kozeny-Carman equation,

\begin{equation}
\text{permeability}(i,j) = \frac{\text{porosity}(i,j)^3}{(1 - \text{porosity}(i,j))^2} \quad \text{Eq. (4.10)}
\end{equation}

**Wall effect**

The increased permeability near the wall regions found in packed beds was simulated by increasing the porosity of the computational cells adjacent to the wall. The porosity increase was imposed on all cells adjacent to the wall to a distance of 1.4 m away.
from the wall. A stepped increment was imposed, ranging from a maximum of 6% at the wall to a minimum of 1% at a distance 1.4 m away from the wall. For example if the porosity at the $i^{th}$ row was found to be 0.5, then the cell adjacent to the wall in the $i^{th}$ row was set as $1.06 \times 0.5 = 0.53$

**Modeling Flow of Air Through the Bed**

The governing equations used for calculating air flow were the Continuity equation (2.24), and the momentum balance in the form of Darcy's laminar flow equation (2.25) described in chapter 2, page 32. Assuming no accumulation of air in the pore spaces of the bed takes place, combining equations 2.24 and 2.25, gives the general steady state equation in pressure as,

$$
\frac{\partial}{\partial x} \left( \frac{\rho K}{\mu} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\rho K}{\mu} \frac{\partial P}{\partial y} \right) - \frac{b_\alpha}{dx dy dz} \frac{dM_e}{d\theta} = 0 \quad \text{Eq. (4.11)}
$$

The products of density, permeability and viscosity together are referred to as the individual conductivity ($c$) to flow in a given cell $(i, j)$. The relationships of overall conductivity ($C$) and individual conductivities ($c$) are shown in table 1, and graphically in Figure 4. The cell resistances ($r$'s) are the reciprocal of the conductivities defined above.

**Table 1. The expressions for individual cell conductivities and overall conductivities used in the calculation of air flow in the compost model.**

<table>
<thead>
<tr>
<th>Cell resistances</th>
<th>Cell conductivities</th>
<th>Overall conductivities</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_0$</td>
<td>$c_{0li,j} = (\rho K/\mu)_{i,j}$</td>
<td>$C_{0li,j} = (c_{0li,j} \times c_{2li-1,j}) / (c_{0li,j} + c_{2li-1,j})$</td>
</tr>
<tr>
<td>$r_1$</td>
<td>$c_{1li,j} = (\rho K/\mu)_{i,j}$</td>
<td>$C_{1li,j} = (c_{1li,j} \times c_{4li,j-1}) / (c_{1li,j} + c_{4li,j-1})$</td>
</tr>
<tr>
<td>$r_2$</td>
<td>$c_{2li,j} = (\rho K/\mu)_{i,j}$</td>
<td>$C_{2li,j} = (c_{2li,j} \times c_{0li+1,j}) / (c_{2li,j} + c_{0li+1,j})$</td>
</tr>
<tr>
<td>$r_3$</td>
<td>$c_{3li,j} = (\rho K/\mu)_{i,j}$</td>
<td>$C_{3li,j} = (c_{3li,j} \times c_{1li,j+1}) / (c_{3li,j} + c_{1li,j+1})$</td>
</tr>
</tbody>
</table>

Note: $C$'s represent the overall conductivities evaluated at node $ij$. 
Figure 4. General nomenclature used in the compost model (a) and the computational procedure for dealing with boundary conditions (b,c).
Writing equation 4.11 in finite difference form for the cell \((i, j)\) we get,

\[
\frac{C_1}{dx} \frac{P(i, j - 1) - P(i, j)}{dx} - \frac{C_3}{dx} \frac{P(i, j) - P(i, j + 1)}{dx} - l_{(\text{in-out})} + \frac{C_0}{dy} \frac{P(i - 1, j) - P(i, j)}{dy} - \frac{C_2}{dy} \frac{P(i, j) - P(i + 1, j)}{dy} - \left[ \frac{b_{\alpha}}{dx \, dy \, dz \, d\theta} \frac{dM_c}{dx} \right]_{\text{gen}} = 0
\]

Eq. (4.12)

expanding equation 4.12 we get,

\[
\frac{C_1}{dx^2} \frac{P(i, j - 1) - P(i, j)}{dx^2} - \frac{C_3}{dx^2} \frac{P(i, j) - P(i, j + 1)}{dx^2} + \frac{C_1}{dy^2} \frac{P(i, j - 1) - P(i, j)}{dy^2} - \frac{C_3}{dy^2} \frac{P(i, j) - P(i, j + 1)}{dy^2} - \left[ \frac{b_{\alpha}}{dx \, dy \, dz \, d\theta} \frac{dM_c}{dx} \right] = 0
\]

Eq. (4.13)

multiplying through by \(dx^2\) and replacing \(dx^2/dy^2\) by \(\lambda\) we get,

\[
[C_1P(i, j - 1) - C_1P(i, j) - C_3P(i, j) + C_3P(i, j + 1)] + \lambda[C_2P(i - 1, j) - C_0P(i, j) - C_2P(i, j) + C_2P(i, j + 1)]
\]

\[
- \left[ \frac{dx \, b_{\alpha}}{dy \, dz \, d\theta} \frac{dM_c}{dz} \right] = 0
\]

Eq. (4.14)

Solving for \(P(i, j)\) in the above equation gives,

\[
P(i, j) = \frac{[C_1P(i, j - 1) + C_3P(i, j + 1)] + \lambda[C_0P(i - 1, j) + C_2P(i, j) + C_2P(i + 1, j)]}{C_1 + C_3 + \lambda[C_0 + C_2]} \left[ \frac{dx \, b_{\alpha}}{dy \, dz \, d\theta} \frac{dM_c}{dz} \right]
\]

Eq. (4.15)
Equation 4.15 is solved iteratively in the profile $i = 1$ to $i_{\text{max}}$, $j = 1$ to $j_{\text{max}}$, until the largest difference in pressures between iterations at any location within the domain becomes less than a defined tolerance $\text{"tol"} = 1.0 \times 10^{-6}$. It was found that with random initial values in the domain, the maximum number of iterations needed to converge was 6000. Convergence was achieved within 10 iterations when the boundary conditions were not changed (i.e. only temperature changes were present).

Figure 5 shows a flow diagram of the steps involved in computation. The first step involves calculation of individual cell conductivities at each node $i, j$ using the relationships given in Table 1. Next the boundary conditions are set as follows:

\begin{equation}
\text{Eq. (4.16)}
\end{equation}

- **Left wall**: $c_3(i, 0) = 0.0$ for $i = 1$ to $i_{\text{max}} - 1$
- **Right wall**: $c_1(i, j_{\text{max}} + 1) = 0.0$

The overall conductivities $C$'s are calculated using the relationships in Table 1, with the exception of rows 1 and $i_{\text{max}}$, representing the air inlet and outlet respectively. The overall conductivities in these cells are as follows:

\begin{equation}
\text{Eq. (4.17)}
\end{equation}

- **Inlet air**: $C_0(1, j) = 2 \times c_0(1, j)$, for $0 < j < j_{\text{max}} + 1$
- **Exit air**: $C_2(i_{\text{max}}, j_{\text{max}}) = 2 \times c_2(i_{\text{max}}, j_{\text{max}})$

The pressures for the boundary are set as, $\text{pressure}(0, j) = \text{pressure}_{\text{in}}$ (assumed pressure drop). The solution proceeds by setting the boundary conditions and iteratively solving for $P(i, j)$. After convergence is reached, the air flow into the bed ($\text{air}_{\text{in}}, \text{kg(DA)/sec}$) for
Figure 5. Flow chart of the iterative computation of the pressure profile, and velocity vectors within the computational domain.
the assumed pressure drop is calculated. The actual pressure drop in the bed is now recalculated using the relation:

\[
\text{real\_pressure} = \frac{\text{fan\_power} \times \text{eff}}{\text{air\_in}/\rho_{\text{amb}}} \quad \text{Eq. (4.18)}
\]

where, \( \text{fan\_power} \) is the defined power consumed by the fan, \( \text{eff} \) is the efficiency of the fan set at 0.6, \( \text{air\_in} \) is the total mass flow of air into the bed, and \( \rho_{\text{amb}} \) is the density of air at the ambient temperature. If the absolute difference between "real\_pressure" and "assumed pressure" was greater than 0.025 Pa, then the assumed pressure was modified as

\[
\text{assumed\_pressure} = \frac{\text{assumed\_pressure} + \text{real\_pressure}}{2} \quad \text{Eq. (4.19)}
\]

the iteration was then repeated by solving for \( P(i,j) \), until convergence. After convergence, the velocities were calculated using the finite difference forms of equation 2.25. A computation check was performed by doing a cumulative mass balance over the whole domain, in order to determine the error associated with finite differencing over the domain cells. The air entering the domain and air leaving the domain were summed over the period from the start of computation till the current time and a running balance was maintained. A similar running balance was maintained on the amount of air mass lost (\( b_{\text{m}} \times \frac{dm_x}{dt} \)) based on the amount of dry matter degradation. Since air does not accumulate in the pore space, the error in computation was the percentage difference between (\( \text{air\_in} + \text{air\_generated} \)) and \( \text{air\_out} \). This value represents a mass balance over the entire period of simulation from start to the current time and is printed out as a percentage.
Modeling Compost Degradation in the Bed

The degradation of dry matter is modeled after the equation presented by Keener et al. (1993a), which is,

\[
\frac{dM_e}{d\theta} = -k(M_e - M_i) \tag{4.20}
\]

where \( M_i \) is the mass of dry matter of compost and \( M_e \) is the equilibrium mass of compost evaluated at time zero. The equation is implemented independently for the case of biosolids and amendments. At all times in the program, the masses, equilibrium masses and degradation rates are calculated separately for biosolids and amendments. The manner of calculation is as follows:

\[
mc_{\_\text{dry}[i][j]_0} + A = mc_{\_\text{dry}[i][j]} + A \theta^*(k*(mc_{\_\text{dry}[i][j]_0} - m_e[i][j])) \tag{4.21}
\]

here \( mc_{\_\text{dry}} \) is the kg of dry matter of biosolids or amendment in the cell (i,j) and \( m_e \) is the corresponding equilibrium dry matter evaluated at time zero as \( m_e = \beta_o * mc_{\_\text{dry}} \).

The factor \( \beta_o \) is the non-decomposable part of the dry matter (Keener et al., 1993a). The factor \( k \) is the degradation rate which is a function of temperature and moisture levels. The equation used to incorporate the temperature and moisture effects on \( k \) is a gaussian curve similar to and based on the data analysis presented by Smith and Eilers (1980). The optimal temperature and moistures were 55°C, and 56%, wb. The relations are presented as equations 4.22 (Temperature effect) and 4.23 (Moisture effect) below:
\[ \phi_1 = [-0.563 + 1.566 \exp(-0.5 \left( \frac{\text{temperature}(i,j) - 55}{22} \right)^2)] \quad \text{Eq. (4.22)} \]

\[ \phi_2 = [-56.967 + 57.977 \exp(-0.5 \left( \frac{\text{mc\_fraction}(i,j) - 0.56}{1.52} \right)^2)] \quad \text{Eq. (4.23)} \]

where the coefficients \( \phi_1 \) and \( \phi_2 \) are correction factors for temperature and moisture optima, thus the degradation rate \( k=\phi_1 \phi_2 k_{\max} \). The value used for \( k_{\max} = 3.4 \times 10^{-6} \) and \( 0.6 \times 10^{-6} \) [per second] were the maximum degradation rate at 55 °C and 56%, (wb) moisture content for biosolids and amendments respectively. The values of \( k_{\max} \) are in the range reported in the literature (Keener et al., 1993a). The parameter \( \text{mc\_fraction} \) is the wet basis moisture content at that cell location expressed as a fraction.

**Modeling Water Generation and Transport in the Bed**

The compost mixture in each cell is composed of dry matter (biosolids and amendments) and water. Calculations are performed on each component separately and the variables are called \( \text{mc\_dry\_s}(i,j), \text{mc\_dry\_a}(i,j) \) and \( \text{mc\_water}(i,j) \).

The moisture transport phenomena modeled are 1) evaporative removal of water by air and 2) generation of water by microbial action. The following equation was used to describe the overall water balance,

\[ \frac{dM_w}{dt} = W_s(i,j-1) \rho(\text{temperature}(i,j-1)) \times V_x(i,j-1) + W_a(i-1,j) \rho(\text{temperature}(i-1,j)) \times V_y(i-1,j) - W_s(i,j) \rho(\text{temperature}(i,j)) \times [V_x(i,j) + V_y(i,j)] + b_\alpha \frac{dM_w}{dt} \]

\[ \text{Eq. (4.24)} \]
where $W_{as}(i,j)$ is the humidity ratio at the corresponding location and is calculated by the following method (ASAE Standards, 1970). The saturated vapor pressure is:

$$p_{vs} = \exp\left(\frac{-5800.2206}{T} + 1.3914993 - 0.048640239*T + 4.1764768e-5*T^2 - 1.4452093e-8*T^3 + 6.5459673*\ln(T)\right)$$

where, $T$ is temperature[i][j]+273.16, and the humidity ratio for a given relative humidity (Rh) is,

$$W_{as}(i, j) = 0.62198 \frac{Rh \cdot p_{vs}}{101325 - Rh \cdot p_{vs}}$$

Eq. (4.26)

Here Rh is the relative humidity and was assumed to be 1.0 (i.e. air saturated) at all cells except the inlet cells, which were defined as ambient relative humidity.

A running cumulative water balance over the whole domain was maintained as a computation check. At the start of the simulation, the total water in the bed was computed and stored as “total_water”, and the total water that can be produced if all dry matter were degraded was computed and stored as “water_start”. The following equations were used:

$$total\_water = \sum_{i,j}[mc\_water(i,j)]$$

Eq. (4.27)

$$water\_start = \sum_{i,j}[mc\_dry\_s(i,j) \cdot b_{cw,s} + mc\_dry\_a(i,j) \cdot b_{cw,a}]$$

Eq. (4.28)

where mc_water(i,j) is the mass of water in each cell based on moisture content, and the coefficients $b_{cw}$'s are the masses of water produced per unit mass of dry matter degraded.
At each time step after the computation of air flows, dry matter loss and water balances are performed, the amount of water remaining in the bed is calculated similar to total_water and is called total_water_remaining, and the amount of water producible based on the remaining dry matter is calculated similar to water_start and is called water_rem. Also, a running sum of the following water transport variables was maintained,

\[
\text{Eq. (4.29)}
\]

\[
\begin{align*}
\text{water}_{\text{in}} &= [\text{del}\_\text{time}\*\text{was(ambient)}\*\text{air}_{\text{in}}] \\
\text{water}_{\text{out}} &= \sum_{i,j} [\text{del}\_\text{time}\*\text{was(i max, j)}\*\text{RHO(temperature(i max, j))}\*\text{dxdz}\*V_y(i max, j)]
\end{align*}
\]

The amount of water generated is calculated in two ways, first as (water_start - water_rem), and second as (water_out - water_in - total_water + total_water_remaining). These two values have to be identical and the percentage difference between them is the computational error.

**Modeling Generation and Transport of Heat in the Bed**

The phenomena modeled in heat transport were 1) sensible heating of air, 2) evaporative cooling of compost by air and 3) conductive transport of heat. It was assumed that air leaving the bed surface was at the temperature of the bed and that air was saturated with water at all points within the bed. This may not be an appropriate assumption and makes room for refinement using a more detailed drying model.
However, due to lack of sufficient data to implement a drying model, this assumption was made.

Conductive transport calculations were performed using cell conductivities and overall conductivities similar to the air flow regime. The conductive flux into any cell is defined as for example,

$$
\left(q_x\right)_w = k' \frac{\Delta T}{\Delta y} = C(i,j) \frac{[T(i,j) - T(i,j)]}{dy}
$$

Eq. (4.30)

Here, $k'$ is the thermal conductivity and is expressed as an overall conductivity $C(i,j)$ which is given in table 2 below, the convention of nomenclature is identical to that used in air flow (Figure 4).

Table 2. The expressions for individual cell conductivities and overall conductivities used in the calculation of heat balance in the compost model.

<table>
<thead>
<tr>
<th>Cell resistances</th>
<th>Cell conductivities</th>
<th>Overall conductivities</th>
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</tr>
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<td>$c_{1i,j} = k_{i,j}$</td>
<td>$C_{1i,j} = (c_{1i,j} * c_{4i,j-1}) / (c_{1i,j} + c_{4i,j-1})$</td>
</tr>
<tr>
<td>$r_2$</td>
<td>$c_{2i,j} = k_{i,j}$</td>
<td>$C_{2i,j} = (c_{2i,j} * c_{0i+1,j}) / (c_{2i,j} + c_{0i+1,j})$</td>
</tr>
<tr>
<td>$r_3$</td>
<td>$c_{3i,j} = k_{i,j}$</td>
<td>$C_{3i,j} = (c_{3i,j} * c_{1i,j+1}) / (c_{3i,j} + c_{1i,j+1})$</td>
</tr>
</tbody>
</table>

The thermal conductivities of compost was set as follows,

$$
k_{\text{compost}}(i,j) = 0.1538 + 0.5114 * \text{mc\_fraction}(i,j)
$$

Eq. (4.31)

Where, mc\_fraction(i,j) is the moisture content on a wet basis at the given cell location.

Equation 4.31 was published by Mears et al. (1975) for thermal conductivity of swine manure compost as a function of its moisture level. The thermal conductivity of concrete
was set at 0.14 W/m-K (Ganic and Hicks, 1991). The enthalpy of moist air was evaluated (ASAE, 1970) as:

\[ \text{evap}_\text{air}(i,j) = [c_{pa} + c_{v} \cdot w_{a}(i,j)] \cdot \text{temperature}(i,j) + l_{v} \cdot w_{a}(i,j) \quad [\text{Joule/kg(DA)}] \]

The constants in the above equation are the specific heat capacity of dry air, \( c_{pa} = 1006.9254 \) [J/kg(DA)], the specific heat capacity of moisture in air, \( c_{v} = 1801.03576 \) [J/kg(H2O)vapor] and the latent heat of vaporization of water, \( l_{v} = 2502535.259 \) [J/kg(H2O) evaporated]. The specific heat capacity of the components of the compost mixture was evaluated using an equation cited by Keener et al. (1993a), as for example in the case of amendments,

\[ c_{p_a} = 1480.0 - 640 \cdot \text{Ash} + 4180 \cdot \text{mc\_fraction\_d}(i,j) \quad [\text{J/Kg(DM)}-\text{°C}] \]

where, Ash is the percentage ash content and \( \text{mc\_fraction\_d} \) is the moisture content of the compost mixture evaluated on a dry basis. The value for biosolids was computed similarly as \( c_{p_s} \).

The overall heat balance therefore becomes,

\[ \left[ m\_\text{dry\_a}(i,j) \cdot c_{p_a} + m\_\text{dry\_s}(i,j) \cdot c_{p_s}\right] \cdot \frac{dT}{d\theta} = \]

\[ \left[ -h_{tc} \cdot s \cdot \frac{dM_{c,s}}{d\theta} - h_{tc} \cdot a \cdot \frac{dM_{c,a}}{d\theta} \right] + \]

\[ \left[ \text{evap\_air}(i, j - 1) \cdot \text{RHO}(\text{temperature}(i, j - 1)) \cdot dy \right] \cdot dz \cdot V_{x}(i, j - 1) \] +

\[ \left[ \text{evap\_air}(i - 1, j) \cdot \text{RHO}(\text{temperature}(i - 1, j)) \cdot dx \right] \cdot dz \cdot V_{y}(i - 1, j) \] -
\[
[\text{evap\_air}(i,j) \times \text{RHO(temperature}(i,j))] \times [dy \times dz \times V_x(i,j) + dx \times dz \times V_y(i,j)] + \\
\frac{C_1(i,j)(T(i,j+1) - T(i,j)) - C_3(i,j)(T(i,j) - T(i,j+1))}{dx} \times dz + \\
\frac{C_2(i,j)(T(i+1,j) - T(i,j)) - C_3(i,j)(T(i,j) - T(i+1,j))}{dy} \times dx + \\
\frac{dx \times dy \times dz}{dx} \times dy \times dz_{\text{(in-out)}} \\
\]

Eq. (4.34)

in the above equation \( T \) refers to the temperature at cell \((i,j)\) in °C, and "evap\_air" is the enthalpy of moist air at the specific temperature, \( h_{tc_s} \), and \( h_{tc_a} \) are the heat of combustion of the biosolids and amendments respectively equal to 23.0, and 19.0 MJ/kg (Keener et al., 1993a).

A calculation check was performed similar to the water balance. Five values were evaluated, namely, heat_start, heat_rem, heat_in, heat_out, and heat_store. At the beginning of the simulation heat_start was evaluated as the total heat producible based on dry matter degradation using the following relation:

\[
\text{heat\_start} = \sum_{i,j} \left[ mc_{\text{dry\_s}}(i,j) \times h_{tc\_s} + mc_{\text{dry\_a}} \times h_{tc\_a} \right] \quad \text{Eq. (4.35)}
\]

At the end of each time step during simulation, the remaining heat producible was calculated identical to equation 4.35 and was stored in heat_rem. The difference (heat_start-heat_rem) is the heat generated based on dry matter loss. This quantity should be identical to the values (heat_out-heat_in+heat_store), and the percentage difference between these two quantities was the computational error. The heat\_in and heat\_store are calculated as follows:
heat_in = \[\text{del_time} \times \text{evap_air(ambient)} \times \text{air_in}\]

heat_store = \sum_{i,j} [mc_{dry_s} \times c_{p_s} + mc_{dry_a} \times c_{p_a}] \times \Delta\text{temperature} \quad \text{Eq. (4.36)}

where \(c_{p_a}, c_{p_s}\) are the heat capacities of the amendment and biosolid fractions of the compost material, and \(\Delta\text{temperature}\) is the increase in temperature of the cell at that location. The heat leaving the system was calculated in two parts, first the conductive losses out of the domain and then the heat removed by air. For calculation purposes, it was assumed that conduction losses out of the system is positive, and therefore the total conductive losses (wall_cond) was evaluated as,

\[
\text{wall\_cond} = \sum_i C_i(i,1) \times dy \times dz \times \frac{T(i,1) - T(\text{ambient})}{dx} + C_3(i,j,\text{max}) \times dy \times dz \times \frac{T(i,\text{max}) - T(\text{ambient})}{dx} + \sum_j C_2(i,\text{max},j) \times dx \times dz \times \frac{T(i,\text{max},j) - T(i,\text{max}+1,j)}{dy} + C_0(i,j) \times dx \times dz \times \frac{T(i,j) - T(\text{ambient})}{dy}
\]

The heat leaving the bed due to enthalpy of air leaving was calculated using evap_air, and the total heat_out was:

\[
\text{heat\_out} = \text{wall\_cond} + \sum_j (\text{del\_time} \times \text{evap\_air(i,\text{max},j}) \times V_y(i,\text{max},j)) \times RHO(\text{temperature(i,\text{max},j)}) \times dx \times dz \quad \text{Eq. (4.38)}
\]
Modeling Generation and Transport of Oxygen in the Bed

The oxygen concentration in ambient air is 20.94% (v/v) or 23.14% (wt/wt). The molecular weight of air is calculated to be 28.96 kg(DA)/kgmol(DA), hence at an ambient temperature of 25 °C, the concentration of oxygen in air is calculated as 0.2735 kg(O₂)/m³(DA). This value was given to the variable "o2_amb" in the program. At the beginning of simulation (time = 0), the mass of oxygen in each cell was calculated as,

\[
\text{mass}_{o2}(i,j) = \text{amb}_{o2} \times \text{porosity}(i,j) \times dx \times dy \times dz \quad \text{Eq. (4.39)}
\]

The overall balance for cell (i,j) was written as,

\[
\frac{d(\text{mass}_{o2})}{d\theta} = \frac{\text{mass}_{o2}(i-1,j) \times dx \times dz \times V_y(i-1,j)}{dx \times dy \times dz \times \text{porosity}(i-1,j)} + \frac{\text{mass}_{o2}(i,j-1) \times dy \times dz \times V_x(i,j-1)}{dx \times dy \times dz \times \text{porosity}(i,j-1)} - \frac{\text{mass}_{o2}(i,j)}{dx \times dy \times dz \times \text{porosity}(i,j)} \times \left[dx \times dz \times V_y(i,j) + dy \times dz \times V_x(i,j)\right] + g_{o2_s} \times \frac{dM_{ox}}{d\theta} + g_{o2_a} \times \frac{dM_{ox}}{d\theta}
\]

here, \(g_{o2_s}\) and \(g_{o2_a}\) are the consumption rates of oxygen for biosolids and amendments, calculated from stoichiometry as 1.35 and 1.84 kg(o2)/kg(DM) (Keener et al., 1993a). The solution to this equation in time was performed using the first-order explicit method described by Keener and Meyer (1982). The equation was written in the first-order form which is,

\[
\frac{dY}{dt} = F(t) - a(t) \times Y(t) \quad \text{Eq. (4.41)}
\]
the solution of this equation will then be,

\[ Y_t = \frac{F_{t-1}}{a_{t-1}} + \left( Y_{t-1} - \frac{F_{t-1}}{a_{t-1}} \right) \exp(-a_{t-1} \Delta t) \]  
Eq. (4.42)

For the oxygen balance equation the terms for \( F(t) \) and \( a(t) \) were,

\[ F(t) = \frac{\text{mass}_\text{o2}(i-1,j) \ast V_y(i-1,j)}{\text{dy} \ast \text{porosity}(i-1,j)} + \frac{\text{mass}_\text{o2}(i,j-1) \ast V_x(i,j-1)}{\text{dx} \ast \text{porosity}(i,j-1)} + \text{g}_\text{o2} \ast s \ast \frac{\text{dM}_\text{c,s}}{\text{d}\theta} \]
\[ + \text{g}_\text{o2} \ast a \ast \frac{\text{dM}_\text{c,s}}{\text{d}\theta} \]

and

\[ a(t) = \frac{\text{dx} \ast V_y(i,j) + \text{dy} \ast V_x(i,j)}{\text{dx} \ast \text{dy} \ast \text{porosity}(i-1,j)} \]

for the inlet row (row 1), the value of \( \text{mass}_\text{o2} \) was set to \( \text{o2}_\text{amb} \) in equation 4.43.

**Validating Model Prediction Using Field Data**

A partial validation of the model was performed using the data collected from the composting reactors at the City of Akron Composting Facility. Temperature and moisture contents were the two predicted variables that were used to validate the model. All parameters except one that were used in the model were obtained from the literature, or from experimental measurements such as the compaction equation coefficients. The parameter that was not available was the horizontal porosity profile. This parameter was adjusted to obtain a reasonable fit between model predictions of temperatures in the bed and the field measurements made.

The initial values of compost material properties, ambient environmental conditions and the aeration schedule were input to the computer model. Predictions of
temperature and moisture profiles in the spatial and temporal domain was compared graphically with the measurements made in the real system in the field. A complete description of the field study is described in the next section titled “Spatio-temporal variation of properties in deep bed composting”.

Simulation of the Composting Environment

A series of simulations were performed to determine effects of environmental variables, operating schedule and material properties on the spatial and temporal variation in degradation rates, moisture content, temperature and oxygen concentrations. Outputs were printed as profiles from the top, middle and bottom of the bed and across the width of the bed. Five point outputs per layer were printed and displayed graphically. Total cumulative errors for each of the balances, fan operating conditions and average degradation rates over the whole bed were also printed. All simulations were performed on the high rate composting period of the first seven days of composting.

Simulations were focussed on understanding the effect of the following variables and conditions:

1. Effect of bed depth
2. Effect of initial moisture content of the compost
3. Effect of inlet (ambient) air temperature, and
4. Effect of exit air recirculation.
SPATIO-TEMPORAL VARIATION OF PROPERTIES IN DEEP BED COMPOSTING

The objective of this part of the research was to quantify the spatial and temporal changes in temperature, moisture content, volatile matter content, particle size distribution, mean particle diameter and compactability of biosolids compost. The compactability, bulk density, and permeability of the compost as a function of time were measured at the start of composting, at the first turn and at the end of composting. All spatial data with the exception of temperature was obtained from 15 locations across the cross-section of the reactor, at the first turn (approx. 7th day), and at load out (approx. 21st day) stages. Spatial sampling was done before the mixing operation. Temperature was logged every 10 minutes, and compactability, permeability and bulk density were measured on a mixed sample after the turning operation.

The data was obtained from the biosolids composting reactors at the city of Akron composting facility during the first 21 days of high rate composting. The data collected were meant to be representative of the conditions occurring in a full scale commercial operation, and hence were obtained during the normal operations of the facility. Since it was decided not to hinder the operation in any manner, some of the data obtained were not complete, due to conflicts of time with the operators.

Two runs were performed, lasting approximately 21 days each. Run 1, representing late winter conditions, lasted between the 3rd and the 22nd of May. The ambient temperature during this run was approximately 18 °C. The second run, Run 2
represented early summer conditions and lasted between 26\textsuperscript{th} June and 12\textsuperscript{th} of July. The ambient temperature during this run was approximately 26 °C.

Sample Collection

Samples were collected at the start of composting (Load-in), and analyzed for moisture content, volatile matter content, particle size distribution and compactability. Moisture content and volatiles were estimated on triplicate samples. Moisture content was measured by drying in an oven at 105 °C for 24 hours, and volatile matter content was estimated by ashing in an oven at 550 °C for approximately 6 hours. Particle size distribution was measured on duplicate samples using the method of Cheremisinoff and Cheremisinoff (1984), described below. Compactability of the compost was measured identically to the experimental procedure described in the first part of this chapter. The compost was not dried to different moisture levels, but was tested at the moisture level as sampled.

The profile samples were collected after approximately 7 days, and 21 days of composting, at the time of the first turn and load-out operations. The turning machine was used to dig a flat (vertical) face into the bed of compost. Samples were collected from up to 15 locations across the cross-section of the reactor as shown in figure 6. Table 3 summarizes data of input materials, dates of sampling, and measurements made using samples for both runs.
Particle Size Distribution and Mean Particle Diameter

For proper determination of particle size distribution, Cheremisinoff and Cheremisinoff (1984) suggest the use of at least five classes (size ranges). The samples are first air dried to a workable consistency (moisture content approximately 40%, wb). Then the material is sieved through a set of standard sieves. The resulting fractions are separately dried and the dry weight is measured. The mean particle diameter in each of the $i^{th}$ ranges is given by

$$d_i = \frac{d_{\text{high}} + d_{\text{low}}}{2}$$

Eq (4.44)

Where $d_{\text{high}}$ and $d_{\text{low}}$ represent the size of the sieves above and below the fraction $i$ respectively. The arithmetic mean value of the particle diameter of the whole sample then is calculated as,

$$d_{\text{ave}} = \sum \left[ \frac{d_i G_i}{G} \right]$$

Eq (4.45)

where $G_i$ is the particle dry weights in each class, and $G$ is the total dry weight of all particle. Table 4 below shows the five classes used in run # 1. For run # 2, the fourth class was further divided into two as : 5.66 to 4.00, and 4.00 to 3.36, and the fifth class was divided into 3.36 to 1.98 and less than 1.98.
Figure 6. Schematic of the domain of sampling. The reactor is 6.1 m (20 ft) wide and 3.0 m (10 ft) deep. Approximate sampling location distances from surface and left wall are given in feet.
Table 3. Summary of Run # 1, and Run # 2 of composting trials of spatial and temporal study of composting parameters.

<table>
<thead>
<tr>
<th>Input Materials</th>
<th>Run # 1</th>
<th>Run # 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MC, %</td>
<td>v/v wt/wt</td>
</tr>
<tr>
<td>Sludge</td>
<td>78.2</td>
<td>1.00 1.00</td>
</tr>
<tr>
<td>Bark</td>
<td>34.8</td>
<td>0.68 0.22</td>
</tr>
<tr>
<td>Sawdust</td>
<td>53.6</td>
<td>0.43 0.18</td>
</tr>
<tr>
<td>Recycle</td>
<td>35.1</td>
<td>2.33 1.09</td>
</tr>
</tbody>
</table>

**First Sample (Load-in)**
- May, 3

**Measurement**:
- Moisture content: Triplicate of Mix
- Volatile content: Triplicate of Mix
- Particle size: Triplicate of Mix

**Second Sample (Turn 1)**
- May, 11

**Measurement**:
- Moisture Profile: 15 locations; Triplicate
- Volatiles Profile: 6 locations; Triplicate
- Particle size Profile: 6 locations; Duplicate
- Compaction: Duplicate of Mix

**Third Sample (Load-out)**
- May, 22

**Measurement**:
- Moisture Profile: 15 locations; Triplicate
- Volatiles Profile: None
- Particle size Profile: 6 locations; Duplicate
- Compaction: Triplicate of Mix
Table 4. Fractions used in the sieve analysis of particle size distribution.

<table>
<thead>
<tr>
<th>Size, mm</th>
<th>25.4 - 19.1</th>
<th>19.1 - 9.5</th>
<th>9.5 to 5.66</th>
<th>5.66 to 3.36</th>
<th>&lt; 3.36</th>
</tr>
</thead>
<tbody>
<tr>
<td>di, mm</td>
<td>22.25</td>
<td>14.30</td>
<td>7.58</td>
<td>4.51</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Two samples from each location was used to determine the particle size distribution and average diameter. Six locations were compared, two locations in each layer (see figure 3), one along the left wall, and one at the center of the bed.

**Continuous Measurements: Temperatures**

Measurements of the bed temperature, ambient temperature and relative humidity, and fan operation were made and recorded to a Campbell Scientific CR21X datalogger once every 10 minutes. Thermocouples were attached to wooden dowels and inserted into the compost to measure bed temperature. Three type T thermocouples were connected to each of five dowels. The dowels were 8 feet long, and sharp pointed at the end. The thermocouple junctions were welded, heat sealed with a cover and taped on the dowel with duct tape. The dowels were inserted into the compost at the start of composting, to a depth of 7 feet such as to get temperature measurements from 15 locations similar to the moisture sampling locations (figure 3). Ambient temperature was measured with a T-type thermocouple probe with its junction held unsupported next to the data logger. The relative humidity of the ambient air was measured using a General Eastern RH 8 probe. The probe was calibrated in the range of 22.5 % to 97.3 % relative humidity using salt solution calibration in the laboratory prior to installation.
Fan Times and Air Flows

The amount of time each of the two fans ran was recorded by connecting the fan circuit to a relay and by monitoring the relay closure. The pressure drop at the point of air entry into the plenum was measured at least once a day using a 0-12 inch U-tube water manometer.

Daily Measurement: Settling Rate

The depth of the bed was estimated by measuring the approximate distance from a datum point on the wall of the reactor, to the top of the compost surface. This depth measurements was obtained once a day until the first turn sampling. The objective of measuring the height versus time was to determine the rate of primary settling of the bed of compost.
COMPACTABILITY AND PERMEABILITY OF COMPOSTS

The particle density of biosolids compost was found to be 1365.7 kg/m$^3$ with a standard deviation of 67.8 kg/m$^3$. The compression curves of the biosolids samples are shown in Figure 7. The volume reduction clearly fits an exponential decay as seen in studies of soil compaction by Dexter (1988). The coefficients of Equation 2.8 for biosolids and cow manure composts and their corresponding standard deviations are presented in Table 5. Figure 8 shows the variation of the compression equation coefficient for biosolids with moisture content. All of the coefficients vary linearly with moisture content, and the line through the data shows the equation of best fit. The variation of pressure drop with increasing superficial velocity are shown in Figure 9. There is a trace of non-linearity at higher compacted states, however the data fitted a linear equation with $R^2 > 0.97$ in all cases. Due to the plastic nature of the material, the material at high moistures showed a greater sensitivity to compressive stress than dry materials.

Air permeability decreased exponentially with increasing compressive stress (Figure 10). Dry materials tended to shrink and hence the fraction of fines increased in these samples. This caused an increase in the dry bulk density and a decrease in porosity,
Figure 7. Compression curve for biosolids compost. Symbols indicate average of three data points. Curve through data points represents best fit compression equation. Parameters of the compression equation are presented in table 5.
Table 5. Table summarizing parameters of Compression and Permeability tests. Compression Equation, and Kozeny-Carman Coefficients, and Particle Density of the two materials tested are presented.

<table>
<thead>
<tr>
<th>Initial Moisture (% wb)</th>
<th>Compression Equation Coefficients</th>
<th>Kozeny Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$h_0$</td>
<td>SD</td>
</tr>
<tr>
<td><strong>Biosolids Compost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Particle density: 1365.7 kg/m$^3$. Standard Deviation (SD): 67.8 kg/m$^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>57.4</td>
<td>0.602</td>
<td>0.011</td>
</tr>
<tr>
<td>53.7</td>
<td>0.644</td>
<td>0.021</td>
</tr>
<tr>
<td>47.6</td>
<td>0.670</td>
<td>0.015</td>
</tr>
<tr>
<td>42.8</td>
<td>0.708</td>
<td>0.019</td>
</tr>
<tr>
<td><strong>Cow Manure Compost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Particle density: 1380.5 kg/m$^3$. Standard Deviation (SD): 80.4 kg/m$^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>73.7</td>
<td>0.604</td>
<td>0.044</td>
</tr>
<tr>
<td>68.4</td>
<td>0.535</td>
<td>0.004</td>
</tr>
<tr>
<td>61.6</td>
<td>0.550</td>
<td>0.048</td>
</tr>
<tr>
<td>57.3</td>
<td>0.560</td>
<td>0.020</td>
</tr>
</tbody>
</table>
Figure 8. Compression equation coefficients for biosolids compost plotted as a function of the initial moisture content of the material. Curve through data points represents a best fit linear equation.
Figure 9. Increase in pressure drop over a biosolids compost sample as a function of superficial velocity. The data was found to satisfying Darcy' law from which the permeability of the material was estimated.
Figure 10. Changes in measured air permeability of biosolids compost with increasing levels of compaction.
resulting in an overall lower air permeability in uncompacted dry samples. As the biosolids material is compressed the velocity term (β in Equation 2.8) affects the rate at which porosity changes and the difference in permeability is reversed. The air permeability is plotted against total air filled porosity in Figure 11. The Kozeny-Carman equation (Equation 2.19) is fit to the data and the lumped parameter C is determined. Table 5 shows the values of the Kozeny-Carman constant (C) and its variability for the four moisture levels.

**Cow Manure Compost Study**

Figure 12 shows the behavior of cow manure compost under compressive stress. In contrast with biosolids compost (Figure 7), there is no consistent influence of increasing moisture levels. Some variation in air permeability was measured on uncompacted samples (Figure 13), but this is not observed once the sample is compressed. The effect of compaction on permeability was similar to biosolids compost showing an exponential decay, but without any noticeable influence of moisture. The value of C are tabulated in Table 5.

Based on the compactability parameters, the expected profiles of free air space and total pressure drop as a function of bed depth are calculated and shown in Figures 14 and 15. Results from Figure 15 suggests that the non-linearity of pressure drop with height is likely to be caused by the non-linear variation in permeability. Hence, although in a large bed of compost the total pressure drop is a power function of the height, for a differential element the pressure drop can be assumed linear and because of the permeability variation the total pressure is a power function.
Figure 11. Measured air permeability as a function of total airfilled porosity. Curve represents the Kozeny-Carman equation fit to the data. The parameter C is estimated from this fit.
Figure 12. Compression curve for cow manure compost. Symbols indicate average of three data points. Curve through data points represents best fit compression equation. Parameters of the compression equation are presented in Table 5.
Figure 13. Changes in measured air permeability of cow manure compost with increasing levels of compaction.
Figure 14. Calculated free air space profiles in a bed of biosolids compost. Calculations are based on parameters estimated from the compression equations, and assuming that all compression is caused by weight of material in the bed.
Figure 15. Calculated total pressure drop in a bed of biosolids compost. Calculation are based on the Kozeny-Carman model and parameters of the model for different moisture contents.
Dramatic increases in total pressure drop are found when moisture levels approach 60%. This explains the reported high pressure drops (greater than 10 inches of water) in deep beds of high moisture compost in commercial systems. In some full scale systems the initial moisture levels of compost can be 65% or above. From Figure 14 the trends indicate that the free air space drastically reduces with depth from the top in such systems. Levels of FAS < 30% can be reached within the first 1.5 m depth. This can be the potential cause for anaerobic zones. Jens and Regan (1973) reported studies showing that the re-aeration capability of compost was substantially reduced when the free air space was less than 28%. Such systems need to consider the advantages of starting at and maintaining lower moisture levels.

Figure 16 shows the anticipated increase in power consumption with increasing moisture content and bed depth. Calculations are based on the analytical model of Keener et al. (1993a), where the airflow is controlled based on the requirement of controlling temperature at 60 °C. Increase in power consumption is based on decreased air permeability caused by increase in bed height.

Effect of rewetting

Figure 17 shows the compaction curve of biosolids compost after rewetting. Although the compost was at 57.6% moisture, it did not compact as the fresh material at the same moisture level. The permeability (Figure 18) however reduced to the same level as the material at 54.7% (wb) as shown in Figure 7. This suggests that, in material that
Figure 16. Calculated unit power consumption in a bed of biosolids compost as a function of increasing depth. Power is evaluated using the equations presented by Keener et al. (1993a) and the data collected in this research. Power increases are due to decrease in permeability caused by compaction.
Figure 17. Variation in compressed heights of biosolids compost rewetted to different moisture levels. Line through the data represents best fit of Compression equation.
Figure 18. Changes in measured air permeability of biosolids compost rewetted to different moisture levels.
was rewet, the airfilled porosity reduces not due to compost aggregate compression, but rather
due to pore blockage caused by water releasing from the absorption sites. Water added to the
material is absorbed at the surface of the particles, and when particles are subjected to pressure,
the water is released into the pore space causing pore blockage.

**NUMERICAL MODEL OF COMPOSTING**

This section outlines the validation results, and simulation results of the numerical model. Model outputs include temperature, moisture, degradation rate, and oxygen concentration profile changes during the first seven days of composting.

**Validation Runs**

Two field trials (run # 1 and # 2) were made in the commercial composting reactors and temperature and moisture profiles were collected during the 21 days of composting. The amount of compostable materials, initial moisture contents, and mixing ratio of amendments were presented earlier in Table 3. Detailed description of procedures used in making measurements, ambient temperature and aeration histories are reported in the section on “Spatio-temporal changes of properties” in the materials and methods chapter and later in this chapter. The validation of the simulation model was performed by simulating runs # 1 and # 2 on the computer and comparing the trends in temperature and moisture profiles with that measured in the bed during the field study.

All material property parameters used during simulations were obtained from the literature and were maintained constant for all simulations. These are presented below in Table
6. Horizontal profile of porosity was the only parameter of the bed that was not available from direct measurement. This was adjusted in order to obtain profiles of temperature that matched that measured in the field.

Table 6. Parameters used in the compost computer model during simulations. These parameters were maintained constant for all simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>b_cr</td>
<td>Coefficient of air utilization, kg/kg</td>
<td>0.31</td>
</tr>
<tr>
<td>b_cw_a</td>
<td>Coefficient of water production for amendments, kg/kg</td>
<td>0.48</td>
</tr>
<tr>
<td>b_cw_s</td>
<td>Coefficient of water production for biosolids, kg/kg</td>
<td>0.75</td>
</tr>
<tr>
<td>beta_a</td>
<td>Undecomposable fraction of amendments</td>
<td>0.55</td>
</tr>
<tr>
<td>beta_s</td>
<td>Undecomposable fraction of biosolids</td>
<td>0.45</td>
</tr>
<tr>
<td>g_o2_a</td>
<td>Oxygen utilization rate of amendments, kg/kg</td>
<td>1.35</td>
</tr>
<tr>
<td>g_o2_s</td>
<td>Oxygen utilization rate of biosolids, kg/kg</td>
<td>1.84</td>
</tr>
<tr>
<td>h_l_c_a</td>
<td>Heat of combustion of amendments, MJ/kg</td>
<td>19.0</td>
</tr>
<tr>
<td>h_l_c_s</td>
<td>Heat of combustion of biosolids, MJ/kg</td>
<td>23.0</td>
</tr>
<tr>
<td>k_c</td>
<td>Thermal conductivity of compost, W/m-K</td>
<td>Eq. 4.31</td>
</tr>
<tr>
<td>k_max_a</td>
<td>Max. degradation rate of amendments, 1/sec</td>
<td>0.6e-6</td>
</tr>
<tr>
<td>k_max_s</td>
<td>Max. degradation rate of biosolids, 1/sec</td>
<td>3.4e-6</td>
</tr>
<tr>
<td>o2_amb</td>
<td>Ambient oxygen mass concentration, kg-Oa/m^3-air</td>
<td>0.2735</td>
</tr>
<tr>
<td>rho_p</td>
<td>Particle density of compost mix, kg/m^3</td>
<td>1365.7</td>
</tr>
<tr>
<td>rho_w</td>
<td>Density of water, kg/m^3</td>
<td>1000.0</td>
</tr>
</tbody>
</table>

In the computer simulation of run # 1, initial moisture was set to 60 %, and the dry mass fraction of amendments and biosolids were set to 33, and 7 % respectively. Porosity in the cells adjacent to the wall was set to be 6 % higher than the middle of the bed. Ambient temperature was set to vary between 16 and 19 °C (based on figure 57), depth of bed was 3.096 m, and the fans were adjusted to deliver enough air to cool the bed similar to the temperature profile found in the field test.

The temperature and moisture profile histories predicted by the simulation run are shown in Figures 19 and 20. The temperature profile obtained resembles field measurements
(Figure 56) increasing rapidly during the first 24 hours, and reaching a maximum of 75 °C, thereafter the temperature drops depending on the amount of air flow. In the field measured values the temperature at the center of the top layer of the bed reached 80 °C, whereas in simulation the maximum temperature reached was 75 °C. This may have been due to a localized region of poor aeration causing the temperature to remain high. Other conditions that were not seen in the simulation was the quick cooling of the bed seen in Figure 56. The temperature at the top region of the bed cooled to below 30 °C within two days, however simulation results predicted three days for a similar cooling. The bottom region of the bed reached a maximum temperature of 50 °C, which was almost 15 °C lower than that measured in the field. During simulations the bed temperature remained at ambient conditions once the bed cooled, however in field conditions it was seen that temperatures increased after the sixth day. Figure 21 shows the air flows set for this simulation. This was based on the measured fan operation schedule during run # 1 of the field test (Figure 58 shown later).

From the moisture profiles in Figure 20, the bottom of the bed showed very little loss in moisture, this was a result of the rapid cooling of the bed. The assumption that the air temperature at any location in the bed is moisture saturated and equal to the bed temperature causes the bottom of the bed to show no drying. Maximum moisture loss occurs at the top of the bed and at the end of 7 days is expected to be 50 % wb. The field measurements varied between 52.9 to 61.6 % along the top of the bed (figure 68), 35.7 to 57.9 % at the middle region and 44.7 to 59.1 at the bottom. The simulation predicted values were closest to
Figure 19. Temperature profile at the top (upper graph), middle (middle graph) and bottom (lower graph) of the bed during simulation of run #1 of the composting field trials. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle).
Figure 20. Moisture profiles in the top, middle and bottom of the bed during simulation of run # 1 of the composting trials. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle).
Figure 21. Fan operation schedule and the amount of air \([\text{kg(DA)/kg(DM\_in)} \cdot \text{hr}]\) flowing through the compost bed during simulation of run # 1 of the composting trials. Fan power refers to the value set as the boundary condition in W per unit area of reactor base.
measured values in the center of the bed. The drying along the wall regions found in field measured moisture profiles were not obtained in the simulation results due to the restrictive assumption of air being moisture saturated at all locations within the bed.

Figure 22 shows the temperature profiles during simulation of run # 2 of the composting trials. In this run initial moisture was 50%, and the dry mass fraction of amendments and biosolids were set to 36, and 14% respectively (calculated from table 3). Porosity in the cells adjacent to the wall was set to be 2% higher than the middle of the bed. Ambient temperature was set to vary between 25 and 27.5°C (refer Figure 63), depth of bed was 3.048 m, and the fans were adjusted based on measured operation sequence shown later in Figure 64. The temperature increase (Figure 22) in the first 24 hours was similar to the field measured conditions (Figure 62), with rapid cooling thereafter predicted. By the end of 3.0 days the bottom and middle layers reached near ambient conditions. The slower cooling in the field conditions could be due to air escaping from the ducts and plenum, which resulted in lesser air flowing through the bed than estimated from the fan curve. This possibility requires further experimental confirmation.

The fans were switched off at the beginning of day 3 resulting in an increase in temperature in the middle and top of the bed (Figure 62), however simulations results showed only an increase in the top of the bed (Figure 22). The middle of the bed had cooled completely to ambient conditions by the end of day 2 and therefore showed no further activity. Simulation results showed the bed cooling off to ambient conditions by the end of 4.5 days, however in field measurements a temperature of 30°C was reached only at the end of 6 days.
Figure 22. Temperature profile at the top (upper graph), middle (middle graph) and bottom (lower graph) of the bed during simulation of run # 2 of the composting field trials. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle)
Figure 23 shows the moisture profiles in the bed top and bottom regions, and Figure 24 shows the fan operating condition during this simulation. Simulation results showed a moisture level of 38% at the top of the bed, however measured values ranged between 34.2 to 46.4% (Figure 69). This behavior was similar to the results of simulation of run #1 where moisture levels were predicted to be lower than measured at the top of the bed, and higher than measured at the bottom of the bed.

The limited validation of the model shows room for improvement in predictions of the drying of the bed. The temperatures profiles predicted have similar shapes and values as measured. The assumption of porosity of the bed being uniform in the center of the bed and higher at the walls is reasonable, however results of simulation compared to measured values indicate that it is possible that the porosity is not a uniform property. Porosity can be higher or lower at local regions and therefore can affect the air flow path and subsequently the temperature and moisture profiles in the bed. Without more direct measurement of the porosity profiles existing the bed, these results were the best attainable. In the remainder of this section, simulations of the effects bed depth, initial moisture, ambient air temperature, air recirculation, and plenum blockage are reported.

Effect of Depth of Bed

In order to compare the overall effects of bed depth two simulations were made using identical material properties such as 55% initial moisture content, and identical fan powers as
Figure 23. Moisture profile at the top (upper graph), middle (middle graph) and bottom (lower graph) of the bed during simulation of run # 2 of the composting field trials. Symbols indicate from left wall to right: zone1 near left wall(+) zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle)
Figure 24. Fan operation schedule indicating the amount of air [kg(DA)/kg(DMwet)-hr] forced through the compost bed during the first 7 days of simulation of the composting in run #2. Fan power refers to the value set as the boundary condition in W per unit area of reactor base.
boundaries. The depth in the first simulation was set at 2.25 m and in the second was 3.5 m. The resulting increase in depth causes two effects, first an increase in compression of the bottom layers, and second a larger amount of material with about the same aeration.

Figure 25 shows the temperature profile at the top, middle and bottom of the 2.25 m deep bed, and Figure 26 shows the same for the 3.5 m deep bed. It is seen from these that the aeration was just enough to maintain the temperature of the top layer at above 70 °C for most of the run. This results in the lower layers being at lower temperatures and hence the overall bed had high activity. In the case of the smaller bed, the aeration resulted in cooling the material at the top of the bed within the first three days. The bottom layer was overaerated and cooled within 24 hours.

Highest dry matter loss was found in the top of the deeper bed (Figure 27). This was because of the higher temperatures, which was not limiting for most of the seven days of composting. In the case of the bed depth 2.25 m, the highest degradation was only 8.5 % (Figure 28) at the top of the bed, compared to about 10 % in the case of 3.5 m bed. However all the degradation was achieved within 2.5 days, as opposed to the 3.5 m bed which had much slower rates. A scheduled turn after 2.5 days could revive the activity and thus larger amount of degradation can be achieved by maintaining the compost beds at lower temperatures.

Another issue to consider is the possibility of anaerobic conditions as seen in the oxygen concentration profiles across the bed (Figure 29, 30). The highest rates of oxygen consumption was at the top of the bed in the initial 24 hour period when maximum degradation
Figure 25. Temperature profile at the top, middle and bottom of the compost bed during simulation #4. Effect of bed depth on overall activity. The bed depth in this simulation is 2.25 m. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle).
Figure 26. Temperature profile at the top, middle and bottom of the compost bed during simulation # 5. Effect of bed depth on overall activity. The bed depth in this simulation is 3.5 m. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle)
Figure 27. Dry matter ratio profiles in simulation # 5, effect of bed depth. Dry matter ratio is expressed as dry matter divided by initial dry matter. Bed depth in this simulation is 3.5 m. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle).
Figure 28. Dry matter ratio profiles in simulation # 4, effect of bed depth. Dry matter ratio is expressed as dry matter divided by initial dry matter. Bed depth in this simulation is 2.25 m. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle).
Figure 29. Oxygen concentration profiles in simulation # 4, effect of bed depth. Bed depth in this simulation is 2.25 m. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle).
Figure 30. Oxygen concentration profiles in simulation #5, effect of bed depth. Bed depth in this simulation is 3.5 m. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle).
was occurring. In the case of the bed with 3.5 m material, the concentration reached a level of 0.05 kg/m³ potentially being anaerobic.

**Effect of Initial Moisture Content**

Five simulations were performed to look at the effect of different initial moisture content. The moisture contents used were 40, 45, 50, 55 and 60 % respectively. The depth of the bed was set at 3.05 m, ambient temperature and relative humidity were 25 °C and 70 %. Figures 31-35 show the fan powers and airflows through the compost. It is seen that although the fan power was set the same in all cases, the amount of air flowing was governed by the permeability of the media which decreases as the initial moisture of the material increases. At the lowest moisture, a fan power of 0.65 W/m² resulted in a flow greater than 0.017 kg/kg-hr, while at 60 % moisture the flow was about 0.0145 kg/kg-hr. This lower flow with increasing moisture content resulted in underaeration of the bed and hence higher temperatures, which further resulted in the fans operating for longer periods of time.

Figures 36 and 37 shows the temperature profile in the bed for the cases of 40 and 60 % moisture levels. The least aerated material (Figure 37) shows the highest temperature and how temperature remains high for all seven days. The dry matter loss was highest at the top of the bed, and Figures 38 and 39 show these values for the corresponding simulations. Relative degradation was highest at 60 % moisture, which was almost a 11 % decrease (Table 7). The case of 40% moisture showed very little dry matter loss, all of which was completed in the first 48 hours. Although 60% moisture produced the highest overall degradation, the additional energy requirement makes the cost per unit dry matter higher than at 55 % moisture level.
Figure 31. Fan operating schedule and amount of air [kg(DA)/kg(DM$_{tot}$)-hr] flowing through the bed of compost in simulation of the effect of initial moisture content. Initial moisture of the material was 40 %, wb.
Figure 32. Fan operating schedule and amount of air flowing \([\text{kg(DA)/kg(DM_{sat})-hr}]\) through the bed of compost in simulation of the effect of initial moisture content. Initial moisture of the material was 45%, wb.
Figure 33. Fan operating schedule and amount of air flowing [kg(DA)/kg(DMmin)-hr] through the bed of compost in simulation of effect of initial moisture content. Initial moisture of the material was 50 %, wb.
Figure 34. Fan operating schedule and amount of air flowing [kg(DA)/kg(DM_{tot})-hr] through the bed of compost in simulation of effect of initial moisture content. Initial moisture of the material was 55%, wb.
Figure 35. Fan operating schedule and amount of air flowing [kg(DA)/kg(DMinit)-hr] through the bed of compost in simulation of effect of initial moisture content. Initial moisture of the material was 60%, wb.
Figure 36. Temperature profile at the top (upper graph), middle (middle graph) and bottom (lower graph) of the bed during simulation of effect of moisture. Initial moisture level was 40 %, wb. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle).
Figure 37. Temperature profile at the top (upper graph), middle (middle graph) and bottom (lower graph) of the bed during simulation of effect of moisture. Initial moisture level was 60 \%, wb. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle).
Figure 38. Dry matter profile ratio in simulation of the effect of initial moisture level. Moisture was set at 40 %, wb. Symbols indicate from left to right: zone1 near left wall(+) , zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle).
Figure 39. Dry matter profile ratio in simulation of the effect of initial moisture level. Moisture was set at 60 %, wb. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle).
At all other moisture levels, the lower regions of the bed had lower total degradation than the top of the bed. The reason for this is that in the case of aerating to maintain the top of the bed at 70 °C, most of the remainder of the bed is in the range of 50-60 °C. If moisture is not limiting this range is the best condition for degradation and therefore the overall degradation in the bed is higher. This suggests a probable reason for the operators in large facilities preferring to aerate the bed to maintain a temperature of 65-70°C, which is usually measured at the surface of the bed.

**Effect of Inlet Air Temperature**

Three levels of temperatures 15, 25, and 40°C were used as temperature for inlet air to the bed. The temperature of 40°C was used to determine the effect of air preheating on the system. In all cases the initial moisture content was set at 55%, and Rh at 70%. Figures 40-42 show the vertical temperature profile in the three cases. As the ambient temperature increases the cooling capacity of the air decreases and hence larger amounts of air are required for cooling (Figures 43-45). When inlet air is 40°C, maximum aeration keeps the temperature of the bed uniform and above 70 °C for day 4. Maximum degradation was found in this case, and the uniformity was also higher. The relative increase in fan power for this and other configurations and operating conditions are shown later in Table 7.

**Effect of Air Recirculation**

Some systems collect the hot and humid air leaving the compost bed and mix this with ambient air to reaerate the bed. This results in air entering the bed to be at temperatures higher
Figure 40. Temperature profile at the top, middle and bottom of the bed during simulation #9, effect of inlet air temperature. Air temperature was 15°C. Symbols indicate from left wall to right: zone1 near left wall(+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle)
Figure 41. Temperature profile at the top, middle and bottom of the bed during simulation #10, effect of inlet air temperature. Air temperature was 25°C. Symbols indicate from left wall to right: zone 1 near left wall (+), zone 2 (open triangle), zone 3 (open circle), zone 4 (filled triangle), and zone 5 near right wall (filled circle)
Figure 42. Temperature profile at the top, middle and bottom of the bed during simulation #11, effect of inlet air temperature. Air temperature was 40°C. Symbols indicate from left wall to right: zone1 near left wall (+), zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle)
Figure 43. Fan power consumed during operation and amount of air supplied [kg(DA)/kg(DMinit)-hr] into the bed of compost during simulation # 9, effect of inlet air temperature. Temperature was set at 15°C.
Figure 44. Fan power consumed during operation and amount of air supplied \([\text{kg(DA)/kg(DMinated)}\text{-hr}]\) into the bed of compost during simulation #10, effect of inlet air temperature. Temperature was set at 25°C.
Figure 45. Fan power consumed during operation and amount of air supplied [kg(DA)/kg(DM\text{substr})-hr] into the bed of compost during simulation #11, effect of inlet air temperature. Temperature was set at 40°C.
than ambient and near saturated with moisture. A simulation of this scenario was made using the inlet air temperature equal 90% the value of the temperature of the air exiting the compost bed, and having a relative humidity of 98%. The oxygen depletion in the air was not computed as the model did not directly relate degradation kinetics to oxygen levels. The results of interest are the uniformity in degradation and the amount of excess air required to maintain the bed temperatures below 70°C.

Figure 46 shows the vertical temperature profile during the first seven days of composting. It is seen that although the aeration was high the temperature decrease was very slow and the vertical profile showed much less variation than when fresh air was used (e.g. Figure 22). The more uniform conditions results in an overall higher degradation. A maximum degradation of 12% of the initial dry matter was seen at the bottom of the bed. As in the case of the preheated air, the degradation was higher at the bottom, as this region was in the more optimal region of degradation, i.e. 45-55°C. Dry matter degradation profiles are presented in Figure 47, and the fan working times and total air flow into the bed are shown in Figure 48. The fan ran at 0.65 W/m² power for four of the seven days similar to the case of the preheated air (Figure 13). Recirculation of air through the bed shows more homogeneous and increased overall degradation. However there is an increase in the amount of air forced through the bed due to the lesser cooling ability of the air. Table 7 shows the comparison of fan energy usage for the different types of systems.
Figure 46. Temperature profile at the top, middle and bottom of the bed during simulation #12, effect of air recirculation. Symbols indicate from left wall to right: zone1 near left wall(+) zone2(open triangle), zone3(open circle), zone4(filled triangle), and zone5 near right wall(filled circle).
Figure 47. Dry matter ratio profile in simulation #12, effect of air recirculation. Dry matter ratio is expressed as dry matter divided by the initial dry matter. Symbols indicate from left wall to right: zone1 near left wall (+), zone2 (open triangle), zone3 (open circle), zone4 (filled triangle), and zone5 near right wall (filled circle).
Figure 48. Fan operating schedule and amount of air flowing [kg(DA)/kg(DM\text{bed})-hr] through the bed of compost during simulation # 12, effect of air recirculation through the bed.
Effect of Plenum Blockage

In large deep bed reactors, frequent replacement of the bark base at the bottom of the bed is necessary. This is done to prevent the possibility of building up of a hard pan. The hard pan builds in the bark base due to leachate collection and repeated compaction of the bark base. This simulation tested the effect of the presence of a hard pan. The hard pan was simulated by setting the permeability of the cells at the bottom center of the bed equal to 10% of its original value (i.e. for \( i=1, j=4..8; \ K(i,j) = 0.1*K(i,j) \)).

Figure 49 shows the temperature profile at the top, middle and bottom of the bed for the case of a restricted bark base. It is seen that the differences at the bottom layers is greatest at around days 2-4, thereafter sufficient cooling is available and hence the temperatures approach ambient across the width of the reactor. In the top and middle layer the difference in temperature across the width of the reactor is high. As much as 15-40°C higher temperatures are seen in the middle regions of the bed. A similar trend is reflected in dry matter ratio profiles shown in Figure 50. The top of the bed shows a difference of 3-5% in dry matter degradation across the width of the reactor. These may not be considered a great difference due to the inherent variability in the material, however this does reflect a possible reason to mix the bed more frequently to avoid isolated regions of low decomposition.

The fan operation and amount of air forced through the bed is shown in Figure 51. Due to the high temperature sensed by the temperature probe that controls the aeration, the fans were operating on high for six out of the seven days. This indicates that a very high degree of channeling was present across the width of the bed. Table 7 shows the energy usage
Figure 49. Temperature profiles at the top, middle and bottom of the compost bed in simulation # 13, effect of plenum blockage. Symbols indicate from left wall to right: zone1 near left wall (+), zone2 (open triangle), zone3 (open circle), zone4 (filled triangle), and zone5 near the right wall (filled circle).
Figure 50. Dry matter ratio profiles at the top, middle and bottom of the compost bed in simulation #13, effect of plenum blockage. Symbols indicate from left wall to right: zone1 near left wall (+), zone2 (open triangle), zone3 (open circle), zone4 (filled triangle), and zone5 near the right wall (filled circle).
Figure 51. Fan operating schedule and amount of air flowing [kg(DA)/kg(DM_{dry})-hr] through the bed of compost in simulation #13, effect of plenum blockage.
expended during this run as compared to other scenarios. The degree of channelling and non-uniformity present indicates that plenum bockage is a significant problem and during operation the reactor plenum has to be checked periodically for non-uniformity.

Effect of initial $\beta$ value

Certain materials are more degradable than others. For example, primary biosolids have a $\beta$ value equal to 0.45, but treated secondary biosolids have a $\beta$ value of 0.865 (Keener et al., 1993a). This difference in the overall decomposable fraction can result in differing scenarios of degradation. Two simulations were performed, the first with a lower $\beta$ value of 0.35, and the second with a higher $\beta$ value of 0.55. All other parameters such as $\beta$ value of amendments, bed depth, initial moisture content, fan operating logic and other simulation setpoints were fixed as shown in Table 6.

Figures 52 and 53 show the dry matter ratio profile for the two cases of $\beta_0 = 0.35$, and 0.55. It is seen that the increase in overall degradation is very marginal (approximately 1%) for the case of $\beta=0.35$ when compared to $\beta=0.55$. Highest differences was found at day 2 -3 in the bottom layer and at day 5 on the top layer. The higher degradability for the case of $\beta=0.35$ resulted in higher temperatures therefore more air was required to keep the bed cool. Figures 54 and 55 shows the fan power used and the amount of air forced through the bed. A total quantitative comparison is shown in table 7.
Figure 52. Dry matter ratio profiles at the top, middle and bottom of the compost bed in simulation #14, effect of varying $\beta$ values. Initial value used was $\beta = 0.35$. Symbols indicate from left wall to right: zone1 near left wall (+), zone2 (open triangle), zone3 (open circle), zone4 (filled triangle), and zone5 near the right wall (filled circle).
Figure 53. Dry matter ratio profiles at the top, middle and bottom of the compost bed in simulation, #15, effect of varying $\beta$ values. Initial value used was $\beta = 0.55$. Symbols indicate from left wall to right: zone1 near left wall (+), zone2 (open triangle), zone3 (open circle), zone4 (filled triangle), and zone5 near the right wall (filled circle).
Table 7. Summary of average temperature, average dry matter ratio and total energy consumed at the end of seven days of composting. Standard deviations (S_d), and coefficient of variation (C_v) for the temperature and dry matter ratio indicate variation within the bed.

<table>
<thead>
<tr>
<th>Effect of bed depth</th>
<th>Bed Temperature (°C)</th>
<th>Dry Matter Ratio</th>
<th>Energy W-hr/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave</td>
<td>S_d</td>
<td>C_v</td>
</tr>
<tr>
<td>depth 2.25 m</td>
<td>23.5</td>
<td>0.4</td>
<td>1.6</td>
</tr>
<tr>
<td>depth 3.50 m</td>
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<td>11.4</td>
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</tr>
<tr>
<td>Eff. of initial moisture</td>
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<td></td>
</tr>
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<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>45 %, wb</td>
<td>23.1</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>50 %, wb</td>
<td>23.4</td>
<td>0.3</td>
<td>1.1</td>
</tr>
<tr>
<td>55 %, wb</td>
<td>23.7</td>
<td>0.5</td>
<td>2.2</td>
</tr>
<tr>
<td>60 %, wb</td>
<td>33.6</td>
<td>16.4</td>
<td>48.7</td>
</tr>
<tr>
<td>Eff. of inlet air temp.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 °C</td>
<td>14.3</td>
<td>1.3</td>
<td>9.0</td>
</tr>
<tr>
<td>25 °C</td>
<td>23.7</td>
<td>0.5</td>
<td>2.2</td>
</tr>
<tr>
<td>40 °C</td>
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<tr>
<td>Eff. of air recirculation</td>
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<td>Eff. of plenum blockage</td>
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<td>46.7</td>
<td>12.0</td>
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<td>Eff. of material type</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>β = 0.35</td>
<td>47.2</td>
<td>7.8</td>
<td>16.6</td>
</tr>
<tr>
<td>β = 0.55</td>
<td>50.6</td>
<td>8.1</td>
<td>16.0</td>
</tr>
</tbody>
</table>

1 Dry matter ratio is the ratio of remaining dry matter to the dry matter at time zero
2 Energy is normalized as W-hr per unit dry matter degraded
   Energy = W-hr / (1-mR_t)M_0, where mR_t is the mass ratio at the end of day 7, and M_0 is initial dry matter at time zero
   Energy computation refers to fan power for a 1 m slice of the bed of compost
3 Depth of bed for these simulations was 3.048 m (10 ft)
4 Inlet air temperature was 25 °C
Figure 54. Fan operating schedule and amount of air flowing [kg(DA)/kg(DM_brit)-hr] through the bed of compost in simulation #14, effect of varying $\beta$ values. Initial value used was $\beta = 0.35$. 
Figure 55. Fan operating schedule and amount of air flowing [kg(DA)/kg(DMbed)-hr] through the bed of compost in simulation #15, effect of varying β values. Initial value used was β = 0.55.
SPATIO-TEMPORAL VARIATION OF PROPERTIES IN DEEP BED COMPOSTING

This part of the experimental research was focused on measuring the physical conditions, such as temperature, moisture, volatile content, and particle size and distribution, that occur during deep bed composting of biosolids. Measurements were made by sampling both spatially and temporally during the 21 day period of high rate composting.

Bed Temperature Profiles and Aeration

Figure 56 shows the temporal variation in temperature at 14 spatial locations across the cross section of the reactor during the first 7 days of composting. The temperature profiles show that at the surface of the bed a highest temperature of 80 °C was reached within 24 hours of composting. Figure 57 shows the ambient air temperature and relative humidity. The temperatures were relatively low varying between 13 and 18 °C except towards the end of the phase when a peak of 22 °C was reached. The aeration provided to the reactor was relatively low (Figure 58) with only one fan operating most of the time. Rapid increase in temperature was seen within the first 24 hours, indicating the highly reactive nature of the material. A clear profile is seen in all three layers (Figure 56) showing the lowest temperatures along the left wall (T-1 and T-2), confirming the short-circuiting of air along this region. The air entry point into the plenum is along the left wall of the reactor. A difference in temperature between the left wall region (T-1, T-6 and T-11) and the center of the bed (T-3, T-4, T-8, T-9 and T-14), were 25 °C, 30 °C and 35 °C at the top, middle and bottom layers respectively.
Figure 56. Temperature profiles measured at the top, middle and bottom of the bed of compost during run #1 of the composting trials prior to first turn. Symbols indicate from left wall to right: zone 1 near left wall (+), zone 2 (open triangle), zone 3 (open circle), zone 4 (filled circle) and zone 5 near right wall (filled circle).
Figure 57. Ambient air temperature and relative humidity profile during run #1 of the composting trials.
Figure 58. Percentage of time the primary and secondary blowers were working during run #1 of composting trials.
Higher aeration during the first 24 hours of composting would have prevented the peak temperatures reached (center of top layer, figure 56) and its associated microbial population kill. Evidence of population destruction is seen by the slower recovery of temperatures in the top layer center location (filled triangle, figure 56) than in other locations of the top layer, during the second peak at day 6. It is possible that the peak temperature of 80 °C has essentially killed the local microbial population, and reheating was therefore slower.

The first turn and mixing of the compost bed was performed at the end of day 7 and therefore data on temperature was not available during this time. Figure 59 shows the temperature profile in the bed during the five days following the first turn. The probes were removed from the compost bed and data collection was terminated on day 13 at the second turn of the compost bed. It is seen that the bottom of the bed (Figure 59) was essentially cold for all the days following the first turn. Both the top and middle layer showed significant horizontal profiles in temperature. The region along the left wall were below 40 °C for most of the run. At the top of the bed as much as 40 °C difference was seen between the left wall region and the rest of the bed. The center of the reactor had the highest temperature in all three layers, exhibiting the typical core heating. Temperatures greater than 70 °C was reached in both the top and middle layer. This indicates that the mixing operation was beneficial to the system as it thoroughly redistributed the material. Cooling along the left wall due to short-circuiting of air was more enhanced in this phase of run # 1.

Figure 60 shows the ambient air conditions and Figure 61 shows the operation of the blowers during this run. The relative humidity varied between 20 and 80 % with an
Figure 59. Temperature profiles measured at the top, middle and bottom of the bed of compost during run #1 of the composting trials following the first turn. Symbols indicate from left wall to right: zone 1 near left wall (+), zone 2 (open triangle), zone 3 (open circle), zone 4 (filled circle) and zone 5 near right wall (filled circle).
average of around 50% for most of the time. Temperature of inlet air was around 19 - 20 °C for most of the time.

Run # 2 was performed between the 26th of June and the 12th of August. Input materials and their moistures are presented in table 3 (Chapter IV, Materials and Methods). The material loaded into the reactor was lower in moisture (48.8 %, SD 0.8 %, wb) compared to run # 1 (60.5 %, SD 2.0 %, wb). It was explained that the bulking agent and other mixes were all at a lower starting moisture due to the more summer like conditions. Temperature increase was identical to run # 1 with a peak of 80 °C reached (Figure 62) within 24 hours of start up. Ambient air conditions are presented in Figure 63. Aeration during this run was set higher, with both fans operating within the first 24 hours peak point (Figure 64). Lesser horizontal variation in temperature is seen in all of the layers, indicating a more uniform air flow and lesser channeling. The bottom layer cooled off early on the second day of composting and remained below 30°C for the rest of period. In the top and middle layer, temperatures in the range of 40 - 60 °C was seen for most of the period. These temperatures are the most optimal environment for composting (Finstein et al., 1983).

More uniform channeling along the walls is seen in the middle layer (Figure 62), with lower temperatures in the T-6 and T-10 locations along the walls. Similar behavior is seen along the top layer wall region. This more uniform airflow in run # 2 is possibly due to the material being at a lower moisture content at the start of the run, thus reducing the overall compaction in the bed and related permeability reductions. Figure 65 shows the temperature profile in run # 2 after the first turn. Figure 66 shows the ambient air conditions and
Figure 60. Ambient temperature and relative humidity during run #1 of compost trials, after first turn.
Figure 61. Percentage of time the blowers were on after the first turn during run # 1 of composting trials.
Figure 62. Temperature profiles measured at the top, middle and bottom of the bed of compost during run #2 of the composting trials prior to first turn. Symbols indicate from left wall to right: zone 1 near left wall (+), zone 2 (open triangle), zone 3 (open circle), zone 4 (filled circle) and zone 5 near right wall (filled circle).
Figure 63. Ambient air temperature and relative humidity profile during run #2 of the composting trials prior to the first turn.
Figure 64. Percentage of time the primary and secondary blowers were working during run # 2 of the composting trials prior to the first turn.
Figure 67 shows the fan operations schedule. Relative to run #1, very small profiles in temperature are seen across the width of the reactor. Temperatures remained low (< 30 °C) in the bottom layer for most of the run. A quick rise in temperature was seen in the middle of day 13, and is likely due to the fact that both fans were switched off (Figure 67) and no aeration was provided for cooling. Following the peak in temperature both fans were operated continuously causing the bed to cool quickly and remain cool. In the top and middle layers the wall regions tended to be approximately 10 °C cooler than the center of the bed.

**Moisture Content Changes and Profiles**

During run #1 the moisture content was measured at the start of the run, at turn one and at load out. A second turn was performed on the bed but it was not possible to collect samples during this turn due to scheduling problems.

Figure 68 shows a graphical representation of the spatial and temporal changes in moisture in the cross-section of the bed during the high rate composting period. A clear indication of higher drying along the left wall is present in the profile prior to turn 1. Although the temperatures in the center of the bed was up to 25 °C higher than along the walls (Figure 56), thus facilitating drying at the center, the moistures along the wall was up to 20 % lower than the central region. This shows that significantly more airflow was present along the wall region, and that relatively less air moved through the center of the bed. In the profile collected at load-out, a lesser spatial variation in moisture is seen. Around 5 to 10 % variation is seen between the left wall and the rest of the bed.
Figure 65. Temperature profiles measured at the top, middle and bottom of the bed of compost during run #2 of the composting trials following the first turn. Symbols indicate from left wall to right: zone 1 near left wall (+), zone 2 (open triangle), zone 3 (open circle), zone 4 (filled circle) and zone 5 near right wall (filled circle).
Figure 66. Ambient temperature and relative humidity during run # 2 following the first turn operation.
Figure 67. Percentage of time the primary and secondary blowers were working during run # 2 following the first turn.
Initial Moisture Content: 60.5%, wb

Before turn # 1 of Compost bed:

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Before Load-out of Compost bed:

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<tr>
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<td>43.1</td>
<td>45.6</td>
<td>41.6</td>
<td>48.7</td>
<td></td>
</tr>
</tbody>
</table>

Figure 68. Changes in moisture content and resulting moisture profiles in run # 1 of the composting trials. Profile is from 45 samples from 15 locations across the cross-section of the reactor. All moistures reported are in % wet basis. Top layer, middle layer and bottom layers are approximately 6 feet, 4 feet and 2 feet from the bottom of the bed.
Significant channeling is suggested by both the moisture profiles and the temperature histories during this run.

During run # 2 the initial moisture content of the material was lower than usual at 48.8 %, wb. This was due to the greater amount of drier amendments and bulking materials such as recycle, bark and sawdust. Figure 69 shows the changes in moisture and resulting profiles in the bed. A more uniform moisture distribution is found at the bottom layer in the first profile. In the top of the bed a 10 % difference is seen from the wall region to the center of the bed, indicating channeling. From the temperature profile in this region (Figure 62) it is seen that the left wall region was 10 °C lower than the remainder of the bed, this suggests that more air passed through this region and larger evaporative cooling occurred. The compost in the bed was found to be very low in moisture preventing the establishment of an active microbial population. Improvements to managing the system would require water addition to maintain a level of at least 50 %, wb.

Volatile Matter Changes and Profiles

Figures 70 and 71 show the changes in volatile matter content and the resulting profiles during run # 1 and 2. The volatile matter content is interpreted here as an indicator of the amount of degradation that occurred in the compost. Complete profiles were not available at sampling hence the results of these tests can only indicate a general trend. Standard deviations in the measurements ranged between 0.5 to 4 %, and therefore results have to be viewed with caution. The general trend indicates that most of the
**Initial Moisture Content**: 48.8 %, wb

### Before turn # 1 of Compost bed:

<table>
<thead>
<tr>
<th></th>
<th>34.2</th>
<th>46.4</th>
<th>40.9</th>
<th>35.7</th>
<th>35.0</th>
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<tbody>
<tr>
<td></td>
<td>38.1</td>
<td>37.2</td>
<td>38.3</td>
<td>36.2</td>
<td>37.7</td>
</tr>
</tbody>
</table>

### Before Load-out of Compost bed:

|     | 27.3 | 32.0 | 28.5 | 28.1 | 25.2 |

Figure 69. Changes in moisture content and resulting moisture profiles in run # 2 of the composting trials. All moistures reported are in % wet basis. Top layer and bottom layers are approximately 6 feet and 2 feet from the bottom of the bed. Two layers were obtained before first turn, and one before load-out. Missing samples were not available due to scheduling problems.
Initial Volatile Matter Content: 79.6%

<table>
<thead>
<tr>
<th>Before turn # 1 of Compost bed:</th>
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<tbody>
<tr>
<td>72.0</td>
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<td>79.1</td>
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<td>77.6</td>
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Figure 70. Changes in volatile matter content and resulting profiles in run # 1 of the composting trials. All numbers reported are as % of dry matter. Top layer, middle layer and bottom layers are approximately 6 feet, 4 feet and 2 feet from the bottom of the bed.
Initial Volatile Matter Content: 78.9%

<table>
<thead>
<tr>
<th>Before turn # 1 of Compost bed:</th>
<th>71.9</th>
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<tr>
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<td>72.1</td>
<td>72.5</td>
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<td></td>
<td>71.4</td>
<td>72.6</td>
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</table>

Figure 71. Changes in volatile matter content and resulting profiles in run # 2 of the composting trials. All numbers reported are as % of dry matter. Top layer, middle layer and bottom layers are approximately 6 feet, 4 feet and 2 feet from the bottom of the bed.
degradation occurs within the first few days of composting. The results of the profile before turn 1 in run # 1 shows that overall degradation was not uniform. The material along the wall region seem to show a higher loss of volatile solids. In run # 2, also, most of the degradation occurred before the first turn, almost no difference was seen in the locations sampled at load-out and the volatile matter in the whole bed at the first turn. The degradation seems to be very uniform, with the entire cross-section (turn 1) being at a volatile solids content around 72 %. The uniformity is also reflected in the temperature profiles (Figures 62, 65) and we can conclude that the lower initial moisture is probably responsible for the more uniform airflow and lesser profiles in temperature and degradation rates.

Mean Particle Diameter and Particle Size Distribution

Average particle size from load-in to load-out and their profiles are shown in Figures 72 and 73 for run # 1 and 2 respectively. It is seen that the mean particle diameter at the start of run # 1 was much higher than in run # 2. This is possibly due to the higher moisture materials forming aggregate clumps more easily. All samples were air dried in the laboratory to approximately 40 % moisture content before particle size estimation, however the method of drying causes the aggregates to remain unbroken. Therefore the moisture content of the material when sampling seems to have an effect on the particle size estimation. At the first turn however the particle sizes in both runs are comparable. In run # 1 the profiles before turn 1 and before load-out seems to indicate a lower particle
Initial Mean Particle Diameter: 8.5 mm

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<th>Before turn #1 of Compost bed:</th>
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<td>6.2</td>
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<td>5.2</td>
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<td>5.6</td>
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<td>3.7</td>
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<td></td>
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<tr>
<td>4.1</td>
<td>5.0</td>
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<td>4.9</td>
<td>5.9</td>
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Figure 72. Changes in mean particle diameter and resulting profiles in run # 1 of the composting trials. Diameters are expressed in mm. Top layer, middle layer and bottom layers are approximately 6 feet, 4 feet and 2 feet from the bottom of the bed.
Initial Mean Particle Diameter: 5.6 mm

Before turn #1 of Compost bed:

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<th>5.2</th>
<th>5.8</th>
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<tbody>
<tr>
<td>4.9</td>
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</table>

Before Load-out of Compost bed:

|      |      |      |
|      | 5.0  | 4.6  |

Figure 73. Changes in mean particle diameter and resulting profiles in run #2 of the composting trials. Diameters are expressed in mm. Top layer, middle layer and bottom layers are approximately 6 feet, 4 feet and 2 feet from the bottom of the bed.
size along the wall relative to the center of the bed. This may be a direct result of higher air flows and more optimal temperatures along the wall acting to increase degradation.

Figure 74 shows the changes in particle size distribution during run # 2 as a cumulative distribution. The curves show that the fraction of total weight of the sample that was below the sieve size given on the X axis. It is seen that all of the sample was less than 25.4 mm (1 inch) at all stages of composting. From earlier discussions on optimal particle size it was stated that an average particle diameter of 0.5 to 1.0 cm is a good trade off between surface area requirements and permeability problems. In both run # 1 (0.85 cm) and run 2 (0.56 cm) it was seen that mean particle size was within this recommended range. From figure 74 it is seen that the smaller size fractions increase as degradation proceeds. The data however does not show very dramatic changes and it is concluded that particle size can be used to understand the requirements of the packed bed, but not as an indicator of degradation.

Compost Bed Settling Measurements

The bed height was measured by approximate visual estimation of the top of the bed and measuring the height from a fixed reference point on the reactor. Figure 75 shows the height of the bed on the first seven days of composting. The height is non-dimensionalized to the initial height. The data shows a general trend similar to the measurements in the compactability tests performed earlier. However it should be
Figure 74. Particle size distribution measured in samples obtained during run # 2 of the composting trials. The samples shown at turn 1 and load out are from location 13 at the center of the bed in the bottom layer.
Figure 75. Bed settling described as non-dimensionalized height of bed at the different days of composting prior to the first turn in run #1 and run #2.
remembered that the settling with time is primary settling and secondary settling and not initial settling. The distinction is made because, primary and secondary settling is caused by moisture migration and the result of bacterial degradation, however initial settling is purely a physical phenomenon of compression.

Compactability and Permeability of Compost

Figure 76 shows the compression curves of the compost material at the load-in, turn 1 and load-out stages of run # 2. As expected from earlier results, the compactability reduces with age and moisture content of the material. It is not possible to discern which one of the two is a greater factor in reducing compactability. The materials were tested at the moisture level as sampled, and no attempt to control or modify the moisture was made. Therefore the effect of moisture level cannot be removed from the influence of age on the material.

The effect of compaction on air permeability, free air space and dry bulk density are shown in Figures 77, 78 and 79. The results of air permeability changes show similar trends to earlier measurements, where the higher moisture material has higher permeability when uncompacted, but compacts more easily than others. At highly compacted states the driest material (i.e load-out) had the highest free air space and correspondingly the highest air permeability. Very little reduction in free air space is seen in the material at 30 % moisture content even at high levels of compaction. The results of the compaction of load-in material (48.8 %, wb) shows that at maximum compaction of 20.7 kPa the free air space continues to remain within safe limits at about 45 %. This result is a confirmation of the predictions from the first section of this research (Figure 11).
Figure 76. Compression curves for the three stages of composting during run #2 of the composting trials. Moisture of materials at load-in, turn 1 and load-out are 48.8%, 36.1%, and 29.8%, wb respectively. Data points presented are average of two replications.
Figure 77. Changes in measured air permeability with compression at different stages of composting during run #2 of the composting trials. Moisture of materials at load-in, turn 1 and load-out are 48.8, 36.1, and 29.8%, wb respectively.
Figure 78. Changes in free air space with compression at different stages of composting during run #2 of the composting trials. Moisture of materials at load-in, turn 1 and load-out are 48.8, 36.1, and 29.8%, wb respectively.
Figure 79. Changes in dry bulk density with compression at different stages of the composting during run #2 of the composting trials. Moisture of materials at load-in, turn 1 and load-out are 48.8, 36.1, and 29.8 %, wb respectively.
CHAPTER VI
CONCLUSIONS, SUMMARY AND RECOMMENDATIONS

An analysis of effects of aeration pathways on the spatial homogeneity and overall effectiveness of in-vessel deep bed composting was performed. Laboratory experiments were performed to relate the moisture level of the material to the compactability and resulting changes in air permeability. A numerical model was implemented for solving the airflow pathways in a two dimensional space and resulting profiles of temperature, moisture, degradation rates and O\textsubscript{2} concentrations were evaluated. A field study was conducted to validate the performance of the numerical model and determine temporal and spatial changes in physical properties of the compost material during the first three weeks of high rate composting.

Compactability and Permeability of Composts

It is shown that the compaction equation and the Kozeny-Carman flow models describe the behavior of the compost media reasonably well. The flow regime follows Darcy's equation of laminar flow within the velocity ranges tested. The compaction equation coefficients were evaluated in the 40 -60 % moisture range and were found to vary linearly (Figure 8).

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Moisture content of the material had very little influence on the compactability in the case of cow manure compost, however biosolids compost showed a progressively higher compactability with increasing moisture. A critical level around 60 %, wb moisture level was observed, above this level, compaction can have very drastic effects in both reducing the free air space and in increasing costs of aeration fan power. When rewet, the compost structural behavior was similar to the low moisture material. There seems to be a very high reduction in permeability when moisture approaches 60 %. It is recognized that the response of the material depends on the type of mixture ratio, however in general for a similar mix the optimal starting moisture should be 48-52 %, wb. Frequent rewetting is recommended.

In the rewetting study performed the material was dried down to below 40 %, wb. Since rewetting is controlled by adsorption and absorption, these being surface phenomena, sufficient time is required for the material to take up all the moisture. If pressure is applied on the particles before complete absorption, the water is released and fills up the pores thus forming leachate and reducing permeability. Hence it would be of advantage to rewet the material when the moisture is still at 50 %, probably even on a daily basis. This recommendation needs to be further tested.

Numerical Model of the Composting System

Validation of the predictions of the numerical model was performed by comparing the temperature and moisture levels measured during the field trials with the model predictions when similar conditions were used as model boundaries. Figures 19 and 22
show the temperature profiles and the corresponding profiles obtained from the field are shown in Figures 56 and 62. Peak temperatures reached, and the point in time when they were reached were very similar to results predicted by the model. In run # 2 the increase in temperature due to the switching off of the fans on day 3 is seen in Figure 66. The similar results was seen only on the top layer of the bed, as the bottom layers had cooled too low for microbial activity to revive. More uniform horizontal profiles were seen in run # 2 when compared to run # 1 and this was simulated successfully by using the different porosity profile in each case. In the simulation of run # 1 the maximum wall porosity was set at 6 % higher than the center, while in the case of simulation run # 2 the corresponding value was 2 %.

The moisture loss model predicted values close to that found in the field measurements in both runs (Figure 20, 23 compared to Figures 68, 69). In run # 2 there was more drying observed, with lowest moistures levels about 35 % wb reached at the end of seven days. The assumption that the air was saturated with moisture at all locations within the bed caused some problem relating to drying. Once the temperature of the bed reduced to a low value then there was no further drying seen. This part of the model can therefore be refined in the future.

Numerous simulations were performed to see the differences in behavior when ambient temperature changes, initial moisture changes, bed depth changes and the effects of cooling air recirculation and plenum blockage. A summary of the different treatments was provided in table 7. As the initial moisture increases the amount of energy required to
keep the bed cool increases tremendously. At 65% initial moisture 292.5 kW-hr (per unit length of reactor) was required as opposed to 126 kW-hr at 45%. The simulation shows that at 65% higher overall degradation can be reached. This is due to the temperature of the bed being at a high temperature throughout the seven days. In the case of 45%, the temperature reaches ambient conditions rather quickly. Mixing of the bed in this case can provide quicker degradation. From the results an initial moisture level in the mid region, around 55% would be recommended.

In the simulations of bed depth effects similar results were found. The energy consumption increased tremendously. However, the deeper bed seemed to show higher degradation, reducing the dry matter ratio to 0.909 at the end of seven days. It seems that the attempt to keep the top layers below 70 °C causes the lower regions to be closer to optimal temperature and hence the overall degradation rates are higher in the bed.

As the temperature of the inlet air is increased the overall spatial degradation increases due to more homogeneity. However the fan energy consumed increases due to more air being required to keep the bed cool. Similar results are seen in the case of recirculating air. The advantage of recirculating air over preheating would be related to drying, as the recirculated air is high in moisture and would not dry the material easily. Blockage of the plenum resulted in a similar increase in energy costs due to the inability to cool the upper regions of the bed.

Addition of a more detailed drying model, determination of compaction parameters for other materials, incorporation of ammonia generation and odor prediction should be
the focus of future work. Additional simulations should be performed to quantify the long term (i.e. 21 days or greater) behavior of the simulation model. Redesign of the plenum, such as incorporation of a perforated baffle to reduce the effect of wall channeling should be studied.

Spatio-Temporal Variations in Properties during Deep Bed Composting

Spatial variation in temperature was found to be significantly reduced in run # 2 relative to run # 1. There was no difference in these two runs between the depth of fill, initial volatile matter content, the structure of the reactor or plenum. The only differences were in the aeration schedule, and the initial moisture content. It is concluded that the higher moisture content (60.5 %) resulted in high compaction therefore leading to uneven flow and easier channeling along the walls. This resulted in very large quantities of air channeling along the walls, and causing higher drying in this region. Also, the center of the bed was above critical temperatures and therefore had very little degradation based on volatile matter content.

Particle size distribution and mean diameters were measured from spatial locations and at different stages of composting. In general the mean particle diameter was found to be an unreliable indicator of degradation. The particle size distribution gives us an idea of the structure of the bed, and it was found that in all cases there was a large fractions of fines, and a large fraction of large particles. This type of mixture is recommend for the construction of biofilters as this gives better permeability properties (Ottengraf, 1986).
Significantly higher and more uniform volatile matter degradation was seen in run # 2 (from 78.9 % to 72 %), however, most of this degradation was completed in the first six days of composting. The material reached moisture limiting conditions thereafter and little degradation was seen.

The changes in compactability and related air permeability with different stages of composting showed results similar to the first part of this research. It was not possible to isolate the effect of moisture from that of the age of the compost. Lower moisture materials showed lesser compactability, and based on earlier analysis this would be another advantage to starting at a lower moisture such as 50 % instead of 60 % initial moisture. This would ensure that the bottom of the 3-3.5 m bed would have a free air space greater than 40 %.

Further studies need to be conducted to evaluate the spatial variation in stability and oxygen uptakes of materials. This would give us a better understanding of the biological activity and the potential anaerobic activity and associated odors. Another area of work would be to determine if the addition of smaller amounts of water more frequently would have an advantage to maintaining the activity of the material for longer periods. These tasks and others toward improving in-vessel composting systems will be left for the future.
BIBLIOGRAPHY


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APPENDIX A

Orifice Plate Calculation of Airflow Through Duct Using Spink’s Equation
The Calculation of the mass flow of air through a pipe can be made using an orifice plate. Spink (1967, eq 45, p 332) has presented the following equation to calculate the flow based on measuring the pressure drop across the orifice plate.

\[ W_h = 359 \cdot S \cdot D^2 \cdot F_s \cdot F_m \cdot F_c \cdot Y \cdot (\gamma \cdot h_w)^{1/2} \]  
Eq (A.1)

where \( W_h \) is the mass flow of air in lbm/hour, and \( h_w \) is the pressure drop across the orifice plate in inches of water. The other coefficients are as follows,

- \( S \) = Coefficient based on ratio of \( d/D \), tabulated in Spink’s handbook (1967), 0.33498
- \( d \) = Diameter of orifice, 1.425 inches
- \( D \) = Diameter of the pipe, 2.067 inches
- \( F_s \) = Ratio of area of primary device at flowing temperature to that at 68 °F, 1.001
- \( F_m \) = Manometer factor, 1.0
- \( F_c \) = Viscosity correction, 1.02
- \( Y \) = Expansion factor, 0.9995
- \( \gamma \) = Density of air at 25 °C, 0.073363 lbm/ft\(^3\)

Based on the above coefficients we have,

\[ W_h = 359 \cdot 0.33498 \cdot 2.067^2 \cdot 1.0205095 \cdot (0.0733663 \cdot h_w)^{1/2} \text{ lbm/hr} \]

which is,

\[ W_h = 142.0233 \cdot (h_w)^{1/2} \text{ lbm/hr} \]
\[ = 2.3671 \cdot (h_w)^{1/2} \text{ lbm/min} \]
\[ Q = 32.2635 \cdot (h_w)^{1/2} \text{ ft}^3/\text{min} \]

Hence at a orifice pressure drop of 0.05 inches of water the volumetric flow rate \( Q \) and the superficial velocity over the sample chamber \( V_s \) are found to be,

\[ Q = 32.02635 \cdot (0.05)^{1/2} = 7.2143 \text{ ft}^3/\text{min} \]
\[ V_s = 7.2143/0.7854 = 9.186 \text{ ft/min} \]