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COLD CLIMATE COMPOSTING: THE INFLUENCES OF SUB-ZERO AMBIENT AND VENTILATING TEMPERATURES

BY

JÜRGEN OTTO FRANKE ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

Bioresource and Food Engineering
Department of Agricultural, Food and Nutritional Science

Edmonton, Alberta
Fall 1997

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UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled *Cold Climate Composting: The Influences of Sub-Zero Ambient and Ventilating Temperatures* submitted by *Jürgen Otto Franke* in partial fulfillment of the requirements for the degree of *Master of Science* in *Bioresource and Food Engineering*.

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Date: September 18, 1997

ABSTRACT

A two phase study was carried out to study the effects of sub-zero temperatures on thermophilic composting processes.

In Phase I, a composting system was designed to study the effects of surrounding and ventilating air of less than 0°C. Measured compost temperatures and respiratory quotients showed that microbial activity decreased.

In Phase II, an adiabatic composting system was designed to study the effects of ventilating air temperatures of -5, +5, and +20°C. Compost temperatures and total heat outputs were measured to test for effects. Compost temperatures in the 20°C treatment decreased the quickest. Mean heat outputs were 22, 21, and 26 $kJ \cdot (gDM)^{-1}$ for the +20, +5, and -5°C treatments respectively. No significant differences were found between total mean values, however, the -5 °C treatment produced significantly higher rates of heat production during peak temperatures. Overall differences in heats suggested that cold ventilating air increase on microbial activity.

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NOMENCLATURE

A = Area, m^2
da = Dry air
DM = Dry matter
h = Enthalpy, kJ·kgda^{-1}
h_a = Specific enthalpy of dry air, kJ·kgda^{-1}
$\dot{h}_f$ = Specific heat of formation, kJ·kg^{-1}
h_g = Specific enthalpy of saturated water vapor, kJ·kg^{-1}
h_{ex} = Enthalpy of the air exiting the composter, kJ·kgda^{-1}
h_{in} = Enthalpy of the air entering the composter, kJ·kgda^{-1}
Δh = Change in enthalpy, kJ·kg^{-1}
k = Thermal conductivity, W·m^{-2}·K^{-1}
L = Length of material, m
$\dot{m}_{H_2O}$ = Mass flow rate of inlet water, kg·sec^{-1}
$\dot{m}_i$ = Mass flow rate of outlet gases and moisture, kg·sec^{-1}
$\dot{m}_{N_2}$ = Mass flow rate of inlet nitrogen, kg·sec^{-1}
$\dot{m}_{O_2}$ = Mass flow rate of inlet oxygen, kg·sec^{-1}
M_{comp} = Mass of compost, kg
M_{H_2O} = Mass of water, kg
n_a = Number of moles of dry air
n_v = Number of moles of water vapor
p_a = Partial pressure of dry air
p_s = Saturated vapor pressure
p_v = Partial pressure of water vapor
P_{atm} = Atmospheric pressure
q_i = Rate of heat into compost, W
q_p = Rate of heat produced by compost, W
q_s = Rate of heat stored in compost, W
q_o = Rate of heat lost from composter, W
q_r = Rate of heat lost through radiation, W
q_{cd} = Rate of heat lost through conduction, W
$q_{cd\text{-}f}$ = Rate of heat lost conductively through the floor and lid of the composter, W
$q_{cd\text{-}w}$ = Rate of heat lost conductively through the walls of the composter, W
q_{ec} = Rate of heat lost through evaporative cooling, W
q_{se} = Rate of heat lost through sensible heating, W
Q = Total heat output from composter, kJ
Q_{cd} = Conductive heat lost from the composter, kJ
$\dot{Q}_{cd}$ = Conductive heat lost per time from the composter, kJ·sec^{-1}
$Q_{cd\text{-}f}$ = Conductive heat lost through the floor and lid of the composter, kJ
$Q_{cd\text{-}w}$ = Conductive heat lost through the walls of the composter, kJ
r_1 = Inner radius of cylinder, m
r_2 = Outer radius of cylinder, m
R = Universal gas constant, 8.31441 J·(g·mol)$^{-1}$·K^{-1}
RH = Relative humidity
T = Temperature, °C or Kelvin

T_{cr} = Temperature in coldroom, °C

dT/dx = Differential of the change in temperature over the change in material thickness

u_{comp} = Internal energy of the compost, $kJ \cdot kg^{-1}$

u_{H_2O} = Internal energy of water, $kJ \cdot kg^{-1}$

v_a = Ventilation flow rate, $L \cdot hr^{-1}$

v_{sa} = Specific volume of air, $m^3 \cdot kg^{-1}$

V = Volume, m^3

VDM = Volatile dry matter

w = Humidity ratio

π = Pi, 3.14159

θ = Time, hr or sec

1. Introduction

Composting is typically defined as a biological process in which bacteria decompose and stabilize organic matter under aerobic conditions and at increased temperatures that are due to the production of heat by the microbial organisms. The composting process is governed by the basic principles of heat and mass transfer, and by biological constraints of living microorganisms (Keener *et al.*, 1993). The optimization of a particular configuration of the composting process has been studied by many researchers (Boelens *et al.*, 1996; Keener *et al.*, 1996; Tseng *et al.*, 1995; Nakasaki *et al.*, 1987; Finstein *et al.*, 1986).

The primary objectives of this study were to learn the key parameters in optimizing the composting process in cold climates. In order to acheive this, it was necessary to quantify the heat produced during the entire process of degradation. Thermal energy yield of the composting process can be derived through the application of thermodynamic principles (Haug, 1993).

1.1. Energy Production in Substrate Biooxidation

Heat generated during composting is a result of the metabolic activity of meso- and thermophilic microorganisms (Finstein and Morris, 1975; Nell and Wiechers, 1978). Metabolic activity, defined as cell production and maintenance (Battley, 1987), is not 100% efficient and allows some energy to be lost as heat.

The oxidation of organic matter involves a complex series of biochemical reactions driven by microbial-induced enzymes. As microorganisms are only active within specie- or strain-specific optimal temperatures and conditions (Atlas and Bartha, 1981), the rate of oxidation, or heat production, is a function of the chemical, physical, and biological properties of the compost. Ambient conditions play an important role in allowing for the optimization of metabolism as well, although this factor is many times forgotten, as it is not a function of the compost substrate. Hence, as optimal conditions are approached, the rate of microbial growth peaks, and the amount of thermal energy released is maximized.

1.2. Cold Climate Composting

Many laboratory-scale composting studies (Suler and Finstein, 1977; Jeris and Regan, 1973; Wiley 1956 and 1957) have repeatedly demonstrated that high temperatures, greater than 60°C, inhibit the activity of compost microorganisms (Kuter et al., 1985). This has been proven to be the maximum range for thermophilic organisms, while the minimum is approximately 45°C. Cold climate composting can be defined as the composting process in the thermophilic temperature range (45 - 60°C) under conditions of ambient and ventilating air temperatures of less than 0°C, where ambient refers to the surrounding conditions. Theoretically, this definition would make the composting process impossible in a cold climate. Yet, it has been shown time and again that organic matter can achieve thermophilic temperatures while ambient temperatures are below freezing (Lynch and Cherry, 1996; Franke *et al.* 1995).

Degradation of organic matter is a naturally occuring process. The application of composting has been limited because of the common misconception that it, too, can occur unaided (Miller, 1993). However, composting is the application of the degradation process, and needs to involve the optimization of all parameters and principles that are integrated together to provide degradation. Much has been learned of the process under normal conditions. Yet, little work has been done in efforts to gain knowledge of the dynamics of the process while being subjected to low temperature conditions. Every individual function and parameter of the composting process needs to be completely understood before the cold climate composting process can be optimized. Composting can be done in colder climates, but optimization could make the composting process in colder climates more feasible economically, and in respect to waste management and minimization.

The objectives in this study were to obtain a better understanding of the influences, if any, of cold ambient and ventilating air on the composting process while maintaining thermophilic temperatures. Effects were to be monitored through the metabolic activity of the composting microorganisms. The entire study was divided into two Phases.

1.2.1. Phase I

Phase I involved the composting of a dairy manure and straw mixture in six large 170L vessels. Two vessels were situated in a warm environment and aerated with warm, ambient air. The remaining four were placed inside a coldroom. Two were ventilated with outside warm air, and two with cold, coldroom air. The objectives of the Phase I study were:

I. Design a composting system to study the response of the composting process when the surrounding and ventilating air temperatures were less than 0°C. Measured parameters included compost and ambient air temperatures, oxygen (O_2) consumption, and carbon dioxide (CO_2) and ammonia (NH_3) production.

II. Gain a simple understanding of the thermodynamic principles exhibited through the application of cold surrounding air and ventilating air.

It was hypothesized that the cold ventilating and ambient air would decrease the rate of activity. The hypothesis was tested by analysis of the measured compost temperatures and gas concentrations.

1.2.2. Phase II

Phase II involved the composting of a dairy manure and straw mixture in six. 9L. adiabatic bench-scale composters. All composters were submerged in a temperature-controlled water bath to eliminate any conductive heat losses. Three treatments were applied with two replicates in each treatment. The three treatments consisted of ventilating the compost with air temperatures of +20, +5, and -5°C. The objectives of the Phase II study were:

I. Design a composting system which could support and reproduce the composting process.

II. Design a composting system which could simulate the composting process inside the core of a typical compost pile or windrow by reducing and possibly eliminating conductive heat losses.

III. Design a composting system to continuously monitor and measure compost, ventilation, and water bath temperatures, oxygen (O_2) consumption, and carbon dioxide (CO_2) and ammonia (NH_3) production, and ventilation rates.

IV. Measure all pertinent compost properties. Included initial and final mass, moisture content, C:N ratio and ash content.

V. Control the flow rate and temperature of the inlet ventilating air.

VI. Measure the total heat output and rate of heat production by the metabolic activity of the microorganism.

It was hypothesized that the cold ventilating air would supress microbial activity. The hypothesis was tested primarily through the analysis of measured quantities of total heat output and rate of heat production. The compost temperature and measured gas concentrations were also considered.

2. Literature Review

2.1. Introduction

Physical modeling is widely used to aid in understanding complex chemical and physical occurrences in nature. In efforts to understand the dynamics of the composting process, many researchers have designed and utilized laboratory-scale, or bench-scale composting models intending to simulate either in-vessel or windrow operations. From a similar, scaled-down version one can gain understanding of the chemical, thermal, physical, and biological aspects of the composting process.

Initially, the composting process was not considered as such, but rather developed from the research of the self-heating of organic materials, which started near the end of the nineteenth century. Wedberg and Rettger (1941) refer to Schloesing in 1884 as one of the first to claim that heating in plant material was a combination of the work of organisms and oxidation. The term 'thermogenesis' was brought about by Cohn (1888) and Cohn (1893) who appears to have been the first to demonstrate the ability of microorganisms to release thermal energy. This led to a rush of studies conducted on microbial heat production in the decompostion of plant material. Most of these initial experiments invariably made use of Dewar vacuum flasks, with perhaps additional insulation or temperature control, as containers for the plant material (Carlyle and Norman, 1941). However, the first apparatus used in experiments on composting was an adiabatic laboratory-scale composter designed by Norman *et al.* (1941).

Since Norman *et al.* (1941), many different designs of physical models have emerged. As well, two different approaches have been used to study the composting process with a laboratory-scale composter: adiabatic and isothermal. Adiabatic conditions can be defined as composting conducted under insulated conditions where any rise in temperature is due to microbial action. Thus it can also be termed self-heating. As conductive losses can potentially account for nine tenths of total heat loss from laboratory-scale composting vessels (Hogan *et al.* 1989), most researchers consider a system to be adiabatic if conductive losses are effectively eliminated. This is opposed to isothermal composters where heat is removed to maintain a set temperature in the composting vessel. As the vessels used in the Phase II study were assumed to be as close to adiabatic as possible, a general review of recent adiabatic composting systems will be made.

Many studies have been done on enthalpy changes accompanying microbial growth using a similar adiabatic design called a microcalorimeter (Wadsö, 1974; Wadsö, 1970; Calvet and Prat, 1963; Forrest, 1961; Kitzinger and Benzinger, 1954). According to Battley (1987) this was started in 1961 by Forrest who published the first of several articles dealing with microbial heat exchange, including a description of a microcalorimeter. However, these researchers focused specifically on heat production from individual bacterial species growing on a simple substrate such as glucose or lactose. As compost is heterogeneous and extremely diverse in both substrate and microbial species, it would be inaccurate to compare these studies with those conducted with compost.

A later focus will be made on those systems, adiabatic or not, used towards objective and quantitative studies of microbial heat production in compost. Few researchers, however, have come up with actual values for the amounts of heat produced in compost. As well, no quantitative studies have yet been done on the effects of low temperature ventilation on heat production in laboratory-scale composting.

2.2. Adiabatic composters

The key factor in any self-heating system is the method used to minimize heat loss from the biologically active organic material. The first scientific self-heating vessel to effectively eliminate heat loss was designed by Norman *et al.* (1941). These researchers used thermocouples and galvanometer amplifiers with a light beam that, when deflected onto a photoconductive cell, actuated the heating mechanism for an insulating water bath. Walker and Harrison (1960) also used this strategy to experiment with the self-heating of wool. Bartholomew and Norman (1953) modified their composting vessel to overcome heat transfer through the vessel wall by suspending the substrate container from the lid of an air-filled pressure cooker. This was then submerged in a thermally-controlled water bath. The air space would have provided an insulating layer, however if the energy required to heat the air between the two containers was found to be negligible or accounted for, is uncertain.

In efforts to minimize conductive heat loss Wiley (1955), (1956), (1957), and Wiley and Pearce (1957b) used a water jacket surrounding the vessel in some experiments and only insulation in others. It is difficult to term the latter physical model adiabatic due to the fact that heat could have been lost through the walls of the composter. Schulze (1958) and (1962) also conducted experiments with well insulated vessels, which thus fall under the same category. Clark *et al.* (1977) and (1978), realizing the potentials of both an adiabatic and isothermal system, designed one of each. But ultimately used the isothermal composting system as it resulted in a more reliable method.

Newer designs involved electronic comparators and thermocouples (Mote and Griffis, 1979) with either comparative transistors (Nell and Wiechers, 1978), or resistive bridges with operational amplifiers (Sikora *et al.* 1983; Sikora and Sowers, 1985). These brought the adiabatic composters to a more sophisticated level. Data accumulated by Sikora *et al.* (1983)

with the adiabatic vessels corresponded closely to data accumulated in the field in a previous experiment (Sikora *et al.* 1981). This indicated a better dynamic similarity to full-scale (i.e. windrow) processes in the newer physical models.

A temperature controlled air bath, instead of a water bath, was used by Kimura and Shimizu (1981). This may not have had as good control over temperature deviations between substrate and surroundings as a water bath because of the lower specific heat of air as opposed to water. However, the system did allow for the continuous monitoring of substrate mass, a feature not often available in other physical models. The adiabatic chamber was suspended from an electronic balance, allowing for the measurement of change in weight of decomposing material.

One of the most sophisticated systems described in the literature consisted of a thermally-controlled air incubator that housed two 0.0141 m^3 composting chambers. This was used to study thermodynamic and matric water potential in laboratory-scale composting ecosystems by Miller (1984). Finstein *et al.*, (1987) used a slightly modified version of Miller's (1984) apparatus to study degradation of industrial hazardous wastes, and Hogan *et al.*, (1989) modified the system again to analyze conductive heat losses by empirically decreasing the surface-area to volume ratio. Although the system was potentially adiabatic, a unique feature of the system (used by Hogan *et al.*, in 1989), was its ability to induce and measure conductive heat losses from the chambers. Temperatures were measured with thermocouples and sent to a data acquisition system that controlled the operation of an incubator heater or cooling fan as required. Although versions differed slightly between researchers, the concept of controlling conductive heat fluxes between the composting chamber and the surrounding air remained the same throughout each experiment.

Some more recent adiabatic systems include simple designs such as that used by Negro and Solano (1996) where 5 L perforated substrate containers were placed in a temperature-controlled climatic chamber. Primary research objectives for Negro and Solano (1996) were to evaluate the quality of different end-products thereby allowing for a more simple design. Atkinson *et al.*, (1996a and b) used an adiabatic system consisting of a 0.028 m^3 vessel placed in a computer-controlled, air-filled climatic chamber to study the biodegradability and microbial activities during composting of poultry litter and municipal solid wastes. Vanbochove *et al.*, (1995) used two simple adiabatic composters containing cow manure that were sampled to characterize the composting stages with respect to the nitrogen cycle.

The number of researchers using adiabatic physical models has increased and the models have improved in quality and accuracy since the design by Norman *et al.*, (1941). The system used by Hogan *et al.*, (1989), however, represents the peak in accuracy of adiabatic physical models as far as measurement and monitoring are concerned. Later systems showed little or no improvement in these areas, as there were few requirements for further developments in measuring and monitoring techniques. With the introduction of computer control, system controls only became more accurate and thus, ultimately, limited by the accuracy and precision of the measuring device and the efficiency of the heating and cooling mechanisms. Beyond a certain point of accuracy however, one must question the entire reasoning of precision required in such systems. Variations between physical, chemical and biological attributes of typical industrial, municipal or agricultural compost substrates are far too great and indeterminable for highly precise analysis to be feasible.

Advancements have been made, though, on insulating and restricting heat loss. In 1995, Iwabuchi *et al.* in a study of heat production rate in the composting of dairy manure modified the version of Bartholomew *et al.*, (1953) creating a layer of insulating air between the substrate container and the water bath. The adiabatic composting apparatus consisted of a 0.001 m^3 stainless steel container having vacuum-insulated walls along the sides and bottom. The lid also incorporated an insulating air space. The entire vessel was submerged in a water bath and the temperature of the water regulated to no greater than 1°C less than the temperature of the compost. This method reportedly showed insignificant heat losses through the vessel wall.

2.3. Thermal aspects of composting ecosystem

2.3.1. Heat Production

Few researchers have carried out successfully quantitative studies of total heat production and the rate of heat production from the activity of microorganisms.

One of the earliest reported values for heat output from decomposing organic material was obtained by Carlyle and Norman (1941) who used Dewar vacuum flasks as adiabatic composters. They estimated maximum heat outputs from wet oat straw at two different temperatures. Reported heat outputs were 39.2 and 22.6 $kJ \cdot (g\ DM)^{-1}$ at 40 and 60 °C, respectively. Walker and Williamson (1957) measured temperatures in bales of slipe wool that corresponded to an average generation of heat of 5.3 $kJ \cdot (g\ DM)^{-1}$. This was calculated in the initial 48 hours in which the temperature in the middle of the bale rose from 17 to 71°C. As heat loss was neglected, the peak rate of heat generation was expected to be in excess of this. Rothbaum (1961), also using slipe wool, reported 22.6, 9.0, 5.1, 2.6, and 0.0 $kJ \cdot (g\ DM)^{-1}$ produced at 37, 60, 70, 74, and 78°C, respectively. These values were analyzed using an adiabatic composter consisting of 2L glass flasks submerged in a water bath. Much work has been done in the area of heat output from specific organic materials, but will not be further reviewed as it pertains little to composting.

Wiley (1957a) was one of the first to measure heat output from compost. While composting garbage with a high lipid content (14.7%), Wiley (1957a) reported total heat outputs of 22.1-28.5 $kJ \cdot (g\ VDM)^{-1}$ and peak heat outputs of 76.7 $J \cdot (g\ VDM)^{-1} \cdot h^{-1}$ at 60°C and a

1h time span. In determining heat production from composting two batches of gin trash harvested a year apart and a mixture of dairy manure and rice hulls, Mote and Griffis (1979) only measured 1.2 and 1.6 kJ·(g DM)$^{-1}$ for the gin trash batches and 2.3 kJ·(g DM)$^{-1}$ from the manure mixture. However, experimental runs lasted only 16 h for the gin trash and 24 h for the manure mixture. This short period could explain the low values reported, as uninhibited compost will maintain thermophilic conditions well beyond these times. Miller (1984) calculated averages of 21.8 and 15.2 kJ·(g DM)$^{-1}$ and peaks of 46.7-54.0 J·(g VDM)$^{-1}$·h^{-1} between 50 and 60°C from a mixture of sewage sludge and wood chips. These values were obtained using the adiabatic system described earlier. Peak rates of 5.8 and 11.6 J·(g VDM)$^{-1}$·h^{-1} at 50°C for oak leaves and 13.1 J·(gVDM)$^{-1}$·h^{-1} at 50°C, both over 24h, were reported by Finstein *et al.*, (1986). Bach *et al.*, (1987) reported a calculated heat output of only 2.5 kJ·(g DM)$^{-1}$ from a commercial-scale composter. Composting mushrooms with straw at temperatures of 72, 55, and 45°C produced peak rates of heat outputs of 8.4, 31.4, and 37.7 J·(gVDM)$^{-1}$·h^{-1} respectively (Miller *et al.*, 1989). These values are in agreement with Rothbaum (1961) who also showed a decrease in heat output with increased temperatures above 60°C. This is possibly due to the fact that optimal conditions for thermophilic bacteria were exceeded and microbial activity had declined. Also, Hogan *et al.*, (1989) reported 14.2 and 16.7 kJ·(g DM)$^{-1}$ from the composting of rice hulls and rice flour in different trials. Peak rates of heat production per unit mass lost were 41.8 J·(gVDM)$^{-1}$·h^{-1} for a period of 12 hours. Iwabuchi *et al.*, (1995) reported a rate of heat output ranging from 20 to 40 J·(gVDM)$^{-1}$·h^{-1} at temperatures of approximately 35 and 60°C respectively while composting dairy manure. The increased rate in heat production under thermophilic conditions does, however, contradict those trends reported by Miller *et al.*, (1989) and Rothbaum (1961).

2.3.2. Cold-climate composting

Many researchers have reported optimal temperature ranges for mesophilic and thermophilic microorganisms in different compost (Jackson and Line, 1997; Rao et al., 1996; Finstein *et al.*, 1986; Strom, 1985; Suler and Finstein, 1977; Dye, 1964; Dye and Rothbaum, 1964; Rothbaum and Dye, 1964; Walker and Harrison, 1960). However, few investigations have been carried out to determine the effects of low ambient temperatures on the composting process and no work has been published on the influences of low ventilating temperatures on the activity of microorganisms.

Initiating microbial activity in compost with temperatures under 20°C has been shown to be difficult and requires more time to activate, even if all other conditions are favorable for decomposition (Mosher and Anderson, 1977; Franke *et al.*, 1995). Composting in sub-zero temperatures has only been reported as successful if there is adequate insulation to reduce conductive heat loss.

Lynch and Cherry (1996) demonstrated that agricultural wastes could be successfully composted in ambient temperatures that ranged from -27 to 15°C. Using the windrow system, they reported that by covering the piles with 0.15 to 0.20 m of finished compost along with a fabric permeable to gases and water vapor and nonpermeable to liquid water, thermophilic conditions were attained. In fact, microbial activity was reported 50 to 80 days after the piles heated up. Lynch and Cherry (1996) were, however, unable to justify the effects of the cover on heat loss and microbial activity. Each pile was also passively aerated with perforated pipes laid perpendicular to the windrow.

Barrington *et al.*, (1994) did not acheive the same success composting solid dairy manure during the winter months. Using a pneumatic evacuator to aerate the piles, they concluded that aerobic activity was not maintained. This method pumped air for approximately

5 minutes, releasing 6 to 7 m^3 of compressed air for each 3 to 4 m^3 of manure (Bloch *et al.*, 1982). The compost was also covered with a black geotextile sheet. Reasons for inactivity were attributed to a high moisture content (maintained at 80% during the entire experiment), and the lack of porosity as well as poor air distribution from the evacuator. The large blast of air was also probably too great and resulted in excessive cooling. Despite the inability to achieve aerobic conditions, Barrington *et al.*, (1994) reported a 50 to 60% loss in nitrogen. However, whether this was simply due to leaching was not clear.

Both Lynch and Cherry (1996) and Barrington *et al.*, (1994) ventilated with cold air, yet both reported different amounts of success in achieving degradation. The differences in the aeration and mixing techniques suggest that Barrington and colleagues did not provide sufficient oxygen on a continuous basis to ensure aerobic conditions and may have had more success had they aerated the pile passively with pipes along with the pneumatic system.

In an experiment to determine the required dimensions of a windrow to maintain microbial activity in sub-zero conditions, Jongejan (1980) reported a required windrow depth of twice the conventional (i.e. 1.5 m). Jongejan tried to simulate conditions within a windrow by placing a 190 L composting vessel within a 380 L thermally controlled bath. Compost consisted of municipal garbage mixed with saw dust. The temperature of the water-antifreeze mixture in the bath was decreased and temperatures measured at different profiles in the composting vessel. The lowest temperature achieved in the water jacket was -30°C, and at a depth of 0.275 m, compost temperatures reported were close to zero. Yet temperatures at the same depth decreased further to -18°C approximately 25 h after the cooling cycle was deactivated and the water bath temperature was reported to be -3°C. Maintaining that a temperature of at least 30°C is required for degradation, Jongejan concluded that a layer of approximately half the radius of a conventional-sized windrow has temperatures too low for decomposition, thus the need to double the radius of the windrow for winter conditions. It is interesting to note Jongejan's design required the ventilating air at 8 to 9 L·min^{-1} to enter the water bath at a few hundred degrees Celsius to provide warm air of 40°C entering the compost mass.

Jongejan's estimate of required insulation may have been exaggerated. Lynch and Cherry (1996) demonstrated thermophilic conditions for a period of 40 days with the windrow system and reported only a small fraction of the pile was below 30°C while ambient temperatures were -8°C. Jongejan also did not account for the decrease in surface-area to volume ratio for larger windrows in estimating required insulation depths. Decreasing this ratio would, in turn, provide a decrease in conductive losses, thereby retaining more heat within the pile. Nor did Jongejan allow for the enormous amounts of heat loss through conduction from his small vessels due to high surface-area to volume ratios. Full-scale systems can only be realistically duplicated in smaller systems if conductive losses are properly controlled (Hogan *et al.*, 1989).

3. Determining Thermal Energy

3.1. *Accounting for Heat Loss*

Heat loss, or specifically heat transfer, is of critical importance in determining a net thermal energy balance. Not only does heat transfer include the flux of thermal energy between the compost matrix and ambient, but also the amount of heat stored within the entire composting mass. The quantity of heat retained during cold-climate composting is extremely important as it is a large determinant of the immediate rate of activity. The ability to store heat by the compost is mostly due to moisture content, owing to the fact that water has a high specific heat capacity compared to most organic matter. Heat generated, that is not stored, is lost through radiation, conduction, evaporative cooling, and sensible heating of air (Miller, 1993).

In view of the composter design and methodology for both Phases I and II studies, radiation was ignored. This is typically assumed for most laboratory composting applications (Finstein *et al.*, 1980).

During the construction of the large 170 L vessels for the Phase I study, efforts were taken to minimize conductive losses by insulating the lids with polyurethane foam (R= 1.92 $m^2 \cdot K \cdot W^{-1}$), and the outside surfaces of the vessels with foil-backed duct insulation (R= 0.9 $m^2 \cdot K \cdot W^{-1}$). This simple method of insulating the composters appeared to be adequate due to the fact that temperatures measured at the center of the vessel were equal to those measured at the same level near the edge of the vessel. The bottoms of the vessels, (i.e. the plenums), were not insulated. This may have been a contributing factor to increasing conductive heat loss from the compost but this was not confirmed. It was felt however, that the air plenum itself offered some insulative protection and any heat lost would not have a large affect on the overall thermal energy balance between the ventilating air and the composting mass.

In designing the bench-scale composters, conductive losses were to be completely eliminated for several reasons. Controlling conductive heat losses in small bench-scale reactors allows full-scale systems to be simulated realistically (Hogan *et al.*, 1989). Eliminating conductive losses also provided the opportunity to accurately measure and analyze the affects of low aeration temperatures and rates. To achieve this properly, the vessel needed to be completely surrounded by a medium maintained at an equal temperature to that of the compost. Water was chosen as the insulative medium instead of air due to its high specific heat content. Although most experimental bench-scale composters in the past have used water (Iwabuchi et al., 1995; Sikora et al., 1983), there have been several experiments utilizing air as an insulative medium (Atkinson et al., 1996; Strom 1985). A water bath was created that enveloped the composter with no less than 50 mm of water on every side (Figure 5.2). An immersion element was installed near the bottom of the bath and actuated by a relay controlled by the computer. This ensured that the temperature differential between the compost and the surrounding water was kept to a minimum. Figure 3.1 shows a typical temperature differential between water bath and compost that was measured for vessel 3 in experiment R8.

Despite the objective to completely eliminate conductive losses, and the small measured temperature differentials between the compost and the water bath, conductive heat fluxes during some experiments were nonetheless found to be of significance ($p < 0.05$) in comparison to the total heat produced (Table 5.4). This was not surprising, as small composting masses with a large surface area to volume ratio will lose a large portion of the total thermal energy through conduction (Clark *et al.*, 1977; Miller, 1993). For this reason the rate of conductive heat loss was analyzed for each composter during each experiment and included in the heat balance.

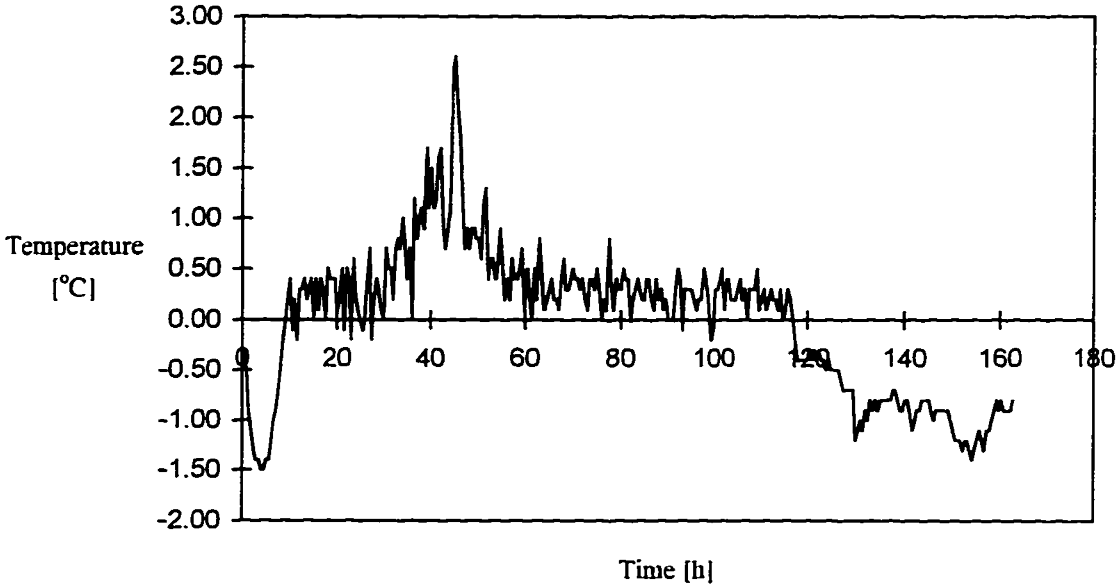

FIGURE 3.1 TEMPERATURE DIFFERENCE OF COMPOST & WATER BATH VS TIME FOR VESSEL THREE, R8

3.2. Calculating Heat Production

A heat balance was done only on each of the six 9 L composters of Phase II, and not of the barrel composters of Phase I. Therefore, the equations listed below were only applied to the Phase II study.

The composting process consists of many complicated and dynamic chemical reactions. Therefore, in order to predict a true heat balance of the composting process, the energy of all the inlet and outlet gases from the composter, as well as energy lost as heat, must be included in the overall balance. This can be written as:

Inlet energy (gases + moisture) + Compost internal energy = Outlet energy (gases + moisture) + Energy lost as heat (3.1)

The typical inlet gases would be oxygen (O_2) and nitrogen (N_2), along with an amount of water in the air. However, it is difficult to list all the outlet gases, and these are therefore written as i terms. Equation 3.1 can be written in long form as:

$$\begin{gathered}\dot{m}_{N_2}\left[\dot{h}_f+\Delta h\right]+\dot{m}_{O_2}\left[\dot{h}_f+\Delta h\right]+\dot{m}_{H_2O}\left[\dot{h}_f+\Delta h\right]+\dot{Q}_{cd}= \\ \frac{d}{d\theta}\left\{M_{comp}u_{comp}+M_{H_2O}u_{H_2O}\right\}+\sum_i\dot{m}_i\left[\dot{h}_f+\Delta h\right]_i\end{gathered} \tag{3.2}$$

where $\dot{m}$ sybolizes the mass flow rate of nitrogen, oxygen, water, and the exhaust gases and outlet moisture. The variable $\dot{h}_f$ is the heat of formation of the respective gas, and Δh indicates the change in enthalpy of the respective gas. The mass of compost and water in the compost is denoted by M_{comp} and M_{H_2O}, respectively, while the internal energy of the compost and water in the compost is denoted by u_{comp} and u_{H_2O}, respectively. These latter terms can be integrated over time θ.

Analyzing the rate of heat production of compost using equation 3.2 can prove to be difficult as all the components of the inlet and, especially, the outlet gases can be difficult and costly to determine. A simpler, although perhaps not as accurate method of writing an energy balance, would be to treat the composting mass as a variable heat source, as opposed to an intricate set of chemical reactions. This would allow an energy balance to be written by simply utilizing the changes in enthalpies in the inlet and outlet air. Differences between methods (i.e. total gas analysis versus enthalpy) can be assumed to be small, as the amounts of certain inlet gases are in direct relationship with the quantities of certain exhaust gases. For example, the amount of oxygen gas consumed by the composting process is always reflected by the amount of carbon dioxide gas released.

Using the changes in enthalpy to determine heat output has been used in many studies in literature (Wiley, 1957a; Mote and Griffis, 1979; Miller, 1984; Finstein *et al.*, 1986; Bach *et al.*, 1987; Miller *et al.*, 1989; Hogan *et al.*, 1989; Iwabuchi *et al.*, 1995). A heat balance involving changes in enthalpy was used as well in this study. The typical approach to the simpler heat balance is derived in the following section.

3.2.1. Heat balance

Heat evolution (thermogenesis) is a direct result of biological activity (Finstein and Morris, 1975; Nell and Wiechers, 1978). The heat evolved is either stored in the compost mass or removed via a combination of several different thermal energy transfer mechanisms. This can be written as a heat balance equation in the form of:

$$q_i + q_p + q_s - q_o = 0 \tag{3.3}$$

where the subscripts on each heat term indicate the rates of heat in, heat produced, heat stored, and heat out, or lost, respectively. The total amount of heat stored over the entire duration of an experimental run was assumed to be zero because the initial and final temperatures of the compost mass were equal to ambient temperatures. This approach gives changes in mass and specific heat of the compost, but the error involved over one heating cycle would be small. The mechanisms of heat loss are radiation, conduction, evaporative cooling, and sensible heating of air:

$$q_o = q_r + q_{cd} + q_{ec} + q_{se} \tag{3.4}$$

where each subscript denotes each mechanism listed above. Substituting equation 3.3 into 3.4 yields:

$$q_i + q_p = q_r + q_{cd} + q_{ec} + q_{se} \tag{3.5}$$

Heat loss in the form of radiation from composting is negligible (Finstein *et al.*, 1980) and was ignored. The rate of heat production in each reactor could, therefore, be determined by measuring the net rate of evaporative cooling and sensible heating of the ventilated air, and the rate of heat lost/gained through conduction. The rate of heat production can be expressed as:

$$q_p = (q_{ec} + q_{se} + q_{cd}) - q_i \tag{3.6}$$

Evaporative cooling is achieved through the uptake of latent heat from the main bulk of water present in the composting mass (Chambers, 1977). Because the mass of water in the compost exceeds the mass of substrate in most composting processes, evaporation contributes to a large part of heat removal. In contrast, the removal of thermal energy through sensible heating is usually low. Sensible heating is a function of specific heats of the materials that make up the composting matrix on a volumetric basis. Water has a high specific heat in respect to other fractions found in compost. Thus, greater amounts of thermal energy will be required to increase the overall temperature of a homogeneous composting mass with a high moisture content.

MacGregor et al. (1981) found that approximately 90% of the thermal energy removed from compost was through evaporation of water vapor, as opposed to only 10% from sensible heating. Bach et al. (1987) reported 0.8% of the total heat removal to be by sensible heating and 34.3% through latent heat of evaporation. Again 10% of overall heat flow was shown to be sensible temperature increase of air by Hogan et al. (1989) and 88% due to latent heat of vaporization.

The fundamentals of latent and sensible heat gain in moist air and thermal conduction in this section were taken from ASHRAE (1981) and ASAE (1987). Analysis used to determine thermal conduction assumed steady state conditions in the compost. As the mean temperature change in the compost occurs over a period of several days, assuming steady state conditions is reasonable.

3.2.1. Conductive heat analysis

The Fourier equation can be applied to conductive heat flow in a compost mass. The general equation can be written as (ASHRAE, 1981):

$$q_{cd} = -kA\frac{dT}{dx} \quad \text{(W)} \tag{3.7}$$

where q_{cd} is the conductive heat flow, k is thermal conductivity of the material, A is the area normal to the direction of heat flow, and $\frac{dT}{dx}$ is the change in temperature in the direction of heat flow (ASHRAE, 1981).

Total conductive heat flow was the sum of the heat fluxes via the walls and through the floor and lid of the composter:

$$q_{cd} = q_{cd-f} + q_{cd-w} \quad \text{(W)} \tag{3.8a}$$

or integrated over time yields:

$$Q_{cd} = Q_{cd-f} + Q_{cd-w} \quad \text{(kJ)} \tag{3.8b}$$

Integrating equation 3.7 in respect to the different geometric shape yields equation 3.9a for heat flowing through a flat wall (i.e. floor and lid), and equation 3.9b for radial flow through a right circular cylinder (i.e. the walls of the composter) (ASHRAE, 1981)[1] .

$$q_{cd-f} = \frac{kA}{L}(T_1 - T_2) \quad \text{(W)} \tag{3.9a}$$

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[1] Two different values for thermal conductivity (k) were used as the walls of two the composters in Phase II consisted of PVC and all the floors and lids consisted of acrylic. As well, plenum walls were insulated with polystyrene to protect ventilating air from heat flows from the water bath. Thermal conductivities were 2.07, 1.42, and 1.13 $W{\cdot}m^{-2}{\cdot}K^{-1}$ for PVC, acrylic, and polystyrene respectively.

$$q_{cd-w} = \frac{2\pi k L(T_1 - T_2)}{\ln \frac{r_2}{r_1}} \quad \text{(W)} \tag{3.9b}$$

In equation 3.9b, $q_{cd\text{-}w}$ is the quantity of heat which flows radially from the inner radius (r_1) to the outer radius (r_2) in the length L. The temperature difference from r_1 to r_2 is (T_1 - T_2). Analysis involving the plenum substituted ventilating air temperatures for T_1, while analysis involving the composting container substituted the compost temperature for T_1.

3.2.2. Latent and sensible heat analysis

The amount of thermal energy in the ventilating air was equated to the latent and sensible heat gain as it passed through the composting mass. The ventilating air was considered to be a mixture of two independent perfect gases: dry air, and water vapor. Each component was assumed to obey the perfect gas law (ASHRAE, 1981):

$$\text{dry air: } p_a V = n_a R T \tag{3.10}$$

$$\text{water vapour: } p_v V = n_v R T \tag{3.11}$$

where p_a is the partial pressure of the dry air and p_v is the partial pressure of water vapor or vapor pressure, V is the total volume of the gas mixture, n_a the number of moles of dry air, n_v is the number of moles of water vapor, R is the universal gas constant, and T is the absolute temperature. Derived from the perfect gas law is the total energy, or enthalpy of the mixture of perfect gases. The enthalpy of the ventilated air equals the sum of the individual partial enthalpies of the mixture of perfect gases, dry air and water vapor. Enthalpy can be written as:

$$h = h_a + w h_g \quad (\text{kJ}\cdot\text{kg dry air}^{-1}) \tag{3.12}$$

where h_a is the specific enthalpy of dry air, w is the humidity ratio and h_g is the specific enthalpy for water vapor (ASHRAE, 1981).

The humidity ratio (w) of the ventilated air, defined as the ratio of the mass of water vapor to the mass of the dry air containing the water vapor, can be determined by the equation (ASHRAE, 1981):

$$w = \frac{0.622 * p_v}{P_{atm} - p_v} \qquad (\text{kg water·kg dry air}^{-1}) \qquad (3.13)$$

where p_v is the partial pressure of water vapor, and P_{atm} is the atmospheric pressure. The partial pressure of water vapor can be defined by the relative humidity (RH) and the saturation vapor pressure (p_s)(ASAE, 1987):

$$RH = \frac{p_v}{p_s} \qquad (3.14)$$

and

$$\ln(\frac{p_s}{\mathrm{R}}) = \frac{\mathrm{A} + \mathrm{B}T + \mathrm{C}T^2 + \mathrm{D}T^3 + \mathrm{E}T^4}{\mathrm{F}T - \mathrm{G}T^2} \qquad (3.15)$$

where:

$\mathrm{R} = 22\,105\,649.25$
$\mathrm{A} = -27\,405.526$
$\mathrm{B} = 97.5413$
$\mathrm{C} = -0.146244$
$\mathrm{D} = 0.12558 \times 10^{-3}$
$\mathrm{E} = -0.48502 \times 10^{-7}$
$\mathrm{F} = 4.34903$
$\mathrm{G} = 0.39381 \times 10^{-2}$

and T is measured in Kelvin.

In the temperature range -10 to 50°C, the specific enthalpies of dry air and of saturated water vapor can be approximated with negligible error to (Çengel and Boles, 1989):

$$h_a \cong T \ (\text{kJ·kg}^{-1}) \qquad (3.16)$$

$$h_g \cong 2501 + 1.80T \ (\text{kJ·kg}^{-1}) \qquad (3.17)$$

where T is the dry bulb temperature (°C) of the mixture. The enthalpy for the ventilated air can therefore can be written as:

$$h = T + w(2501 + 1.805T) \text{ (kJ·kg of dry air}^{-1}\text{)} \tag{3.18}$$

Due to the high rate of evaporative cooling in the composters, the exhaust air was assumed to be 100% saturated. Therefore, the saturation pressure (p_s) equaled the partial pressure of the water vapor (p_v) and the relative humidity (RH) = 1.0. Also, the saturation pressure (p_s) of the exhaust was calculated based on the temperature directly inside the composter, while the humidity ratio (w) of the inlet air was calculated based on the partial pressure of the water vapor and the relative humidity of the air in the coldroom. However, if the temperature in the coldroom was less than 0°C, the partial pressure of the water vapor of the inlet air was assumed to equal the saturation pressure in the coldroom. The relative humidity of the air in the coldroom was determined from dry bulb and wet bulb temperatures measured with a sling psychrometer (Model CP-147, Environmental Tectonics Corporation, Southhampton, PA) when the room temperature was greater than 0°C.

The thermal energy produced by the microbial activity over time θ equals the integral of the difference in enthalpies of the exhaust gases and that of the inlet ventilation air multiplied by the mass flow rate of the air, or the flow rate divided by the specific volume of the air, $v_{sa}(\theta)$:

$$\int dQ = \int \left(\frac{v_a(\theta) * \left(h_{ex}(\theta) - h_{in}(\theta)\right)}{v_{sa}(\theta)} \right) d\theta \text{ (kJ)} \tag{3.19}$$

where $v_a(\theta)$ is the flow rate of the aerated air in L·hr^{-1} at time θ. Specific volume (v_{sa}) is defined as:

$$v_{sa} = \frac{0.287 * T_{cr}}{P_{atm} - p_v} \text{ (m}^3\text{·kg dry air}^{-1}\text{)} \tag{3.20}$$

where T_{cr} is the temperature (°C) in the coldroom, and p_v is the partial pressure of the water vapor in the coldroom. As mentioned, the partial pressure of the water vapor was set equal to the saturation pressure if the temperature in the coldroom was less than 0°C.

3.2.3. Total heat analysis

Equation 3.20 can be integrated over time and substituted into equation 3.6, the overall heat balance of the composting process in the Phase II vessels. Substituting equation 3.8b into 3.6 as well yields the total amount of heat produced from the metabolic activity of the composting microorganisms:

$$Q = \left(\frac{v_a * \left(h_{ex} - h_{in}\right)}{v_{sa}} \right) + \left(Q_{cd-w} + Q_{cd-f}\right) \quad \text{(kJ)} \qquad (3.21)$$

Both equations 3.21 and 3.6 yield total thermal energy produced in the compost.

4. Phase I - Large Vessel Cold Climate Composting

4.1. Experimental design

Six barrel type composters were designed and constructed to study the effects of low ambient and ventilative temperatures on the composting process. The experiments were set up as a nested factorial design to test the hypothesis that sub-zero ambient and ventilative temperatures reduce the activity of microorganism in compost exhibiting thermophilic conditions at a faster rate than ambient temperatures (20°C).

The experiment consisted of three treatments with replications of each treatment. The first treatment was the control where compost was ventilated with ambient air and placed in an environment with ambient conditions (warm-warm). Treatment's two and three were ventilating with ambient air in a cold environment (warm-cold) and ventilating with cold air in a cold environment (cold-cold). The second and third treatment required the four vessels to be placed in a cold room; two ventilated with outside ambient air and two with sub-zero cold-room air. These treatments were not initiated until the compost in each vessel had reached thermophilic conditions (55°C).

Compost temperatures, as well as O_2 consumption, CO_2 and NH_3 production were continously measured, monitored and stored.

4.2. Materials and Methods

The layout of the entire system for Phase I of the cold-climate composting studies is shown in Fig. 4.1. Each component of the system labeled in Figure 4.1 is described below.

4.2.1. Large Vessel Composters

Six 170 L plastic barrels (927 mm in height with a mean diameter of 483 mm) were used as composting vessels. At the bottom of each composter a 27 L ventilation plenum was established with a circular steel grate supported on four 150 mm legs. This space allowed air to be circulated evenly to all areas beneath the compost providing optimal and uniform air flow through the mixture (Figure 4.2).

To help maintain stable temperatures for active decomposition each composter was insulated. The sides of the barrels were insulated with 30 mm of foil-backed fiberglass duct insulation ($R=0.9\ m^2 \cdot K \cdot W^{-1}$) and, inside every lid, a layer of expanding polyurethane foam sealant ($R=1.92\ m^2 \cdot K \cdot W^{-1}$) was sprayed to a depth of 30 to 50 mm. The bottoms of the vessels were not insulated.

The objective was to partially implement the Rutgers Process to control compost temperature. This temperature control strategy was first used by Finstein at Rutgers University (Kuter *et al.*, 1985). Labelled the Rutgers Process, temperature control is achieved through the removal of heat via ventilation that is controlled by a temperature feedback system. As well, to ensure sufficient O_2 concentrations during the initial temperature rise of the compost ($> 10\%$), the Rutgers Process ventilates according to a timer until control temperatures are achieved. A high volume fan operating through a temperature feedback control system was used for the Phase I study. However, rather than operating the same fan on a timer during the onset of the process, a low volume air pump operating continuously was used to ensure that sufficient O_2 was available for uninhibited metabolic respiration. Thus, two air supply lines entered each vessel approximately 40 mm from the floor (Figure 4.2); a high volume and a low volume line. Aquarium pumps (Maxima, Rolf C. Hagen Inc., Montreal, Quebec) were used to deliver air at 3 $L \cdot min^{-1}$ continuously (low volume supply) to each vessel through 6.4 mm OD flexible polyethylene line. The value of

3 $L \cdot min^{-1}$, or 5.5 $L \cdot kg^{-1} \cdot hr^{-1}$ initial dry matter, was the air flow rate found to be typical (Ashbolt and Line, 1982; Bach *et al.*, 1987; Strom, 1978; Wiley, 1955, 1956, 1957). Each pair of composters shared an aquarium pump.

The high volume fans consisted of six centrifugal fans (RB5, Rotom, Bickering, Ontario), each rated at 0.4 amps with a maximum speed of 1600 rpm, and were controlled by software through feedback from the compost temperature sensors. These supplied 30 $L \cdot min^{-1}$ of air to each vessel if the average temperature of the compost exceeded a maximum control temperature. This flow rate was delivered through a 50 mm ID rigid PVC pipe. The sections of pipe located inside the vessels were perforated with an array of 7 mm diameter holes along both the sides and the bottom. The end of the PVC pipe was sealed. The low volume and the high volume ventilation lines for vessel numbers three and four (warm-cold treatment) were insulated with 0.30 m of fiberglass pipe isulation ($R=0.9\ m^2 \cdot {}^\circ C \cdot W^{-1}$), as these composters were located in the coldroom and were required to be ventilated with ambient air

Manually-actuated valves were located on both the 50 mm and 6.4 mm lines to adjust the exact amount of air being delivered to the vessels. Needle valves on the 3 $L \cdot min^{-1}$ air line were used with in-line rotameters (7641T/605, Matheson, Montgomeryville, PA) to control the continuous air supply rate. On the larger PVC pipes an anemometer (Velocicalc 8350, TSI, St. Paul, MN) was used to measure the velocity of the air and hence to calibrate the ball valves used for flow control. Velocities were measured at a straight section of pipe downstream of flow-straightening vanes. A check valve was also placed on each of the pipes to prevent back-flow from the low-volume pumps when the high-volume fans were not in operation.

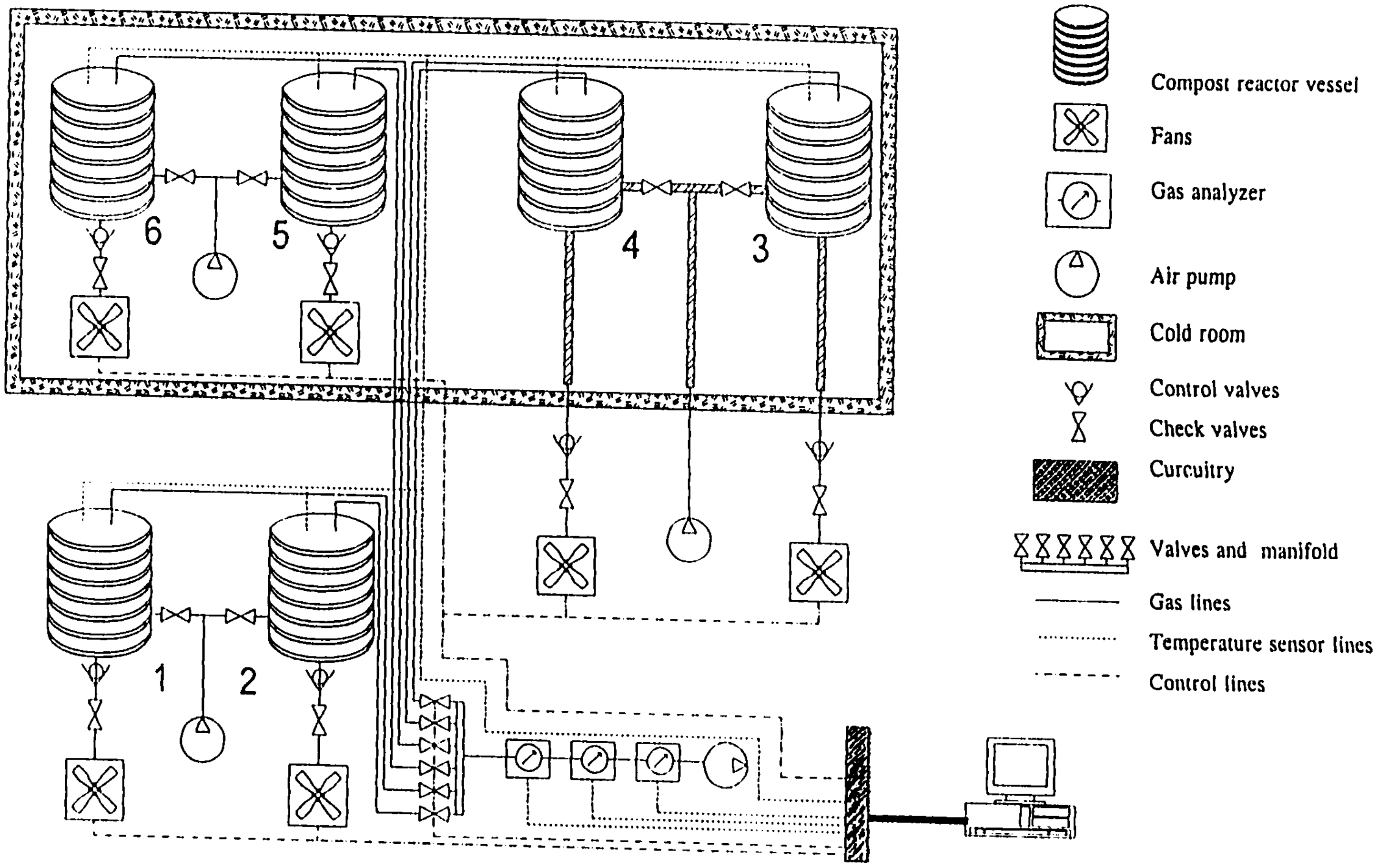

FIGURE 4.1 PHASE I COLD CLIMATE COMPOSTING SYSTEM

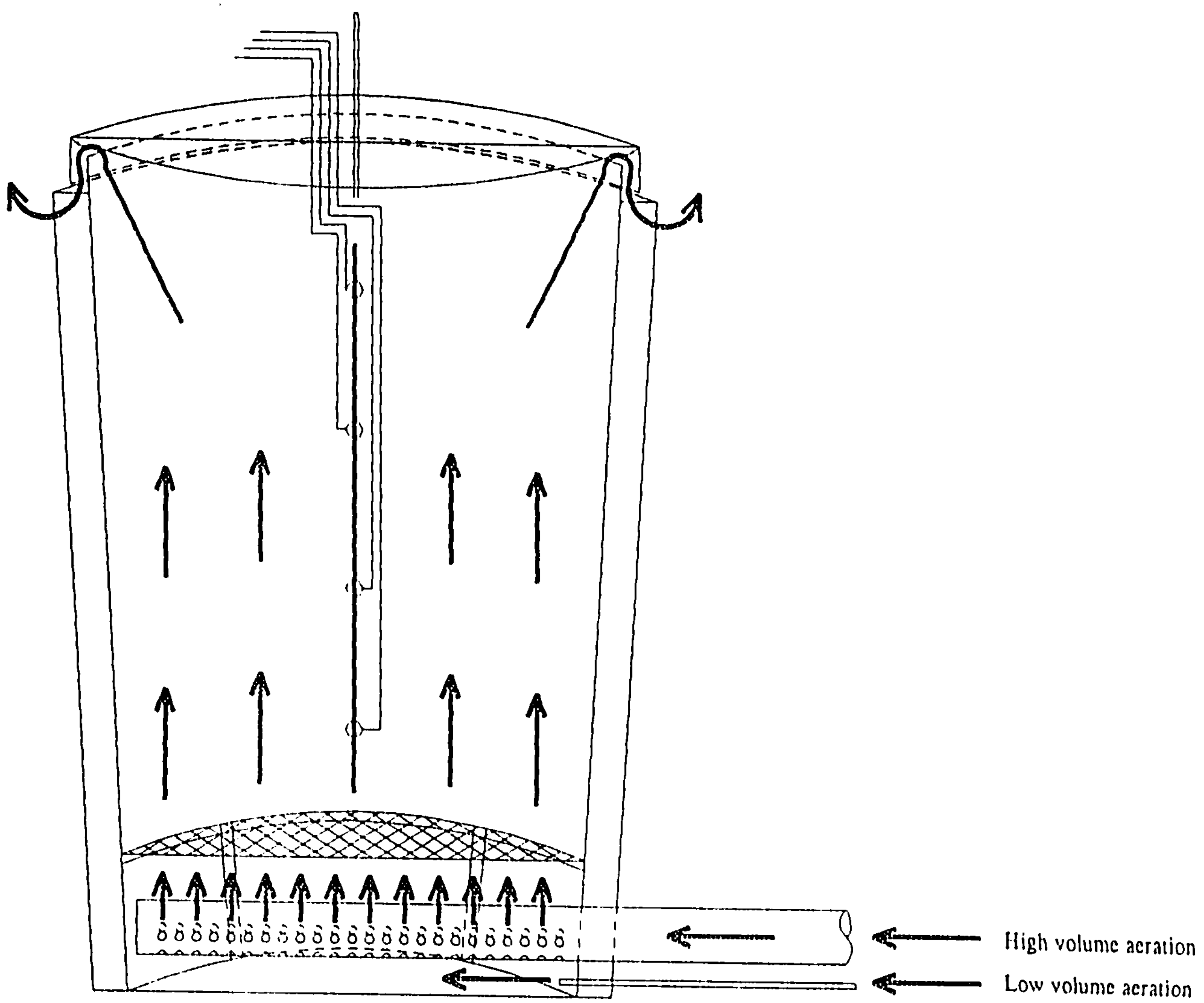

FIGURE 4.2 PHASE I COMPOSTER

The entire air supply system was designed to aerate the compost from the bottom up to the top. Since the natural convection of the air inside the compost would be enhanced by this flow, all areas of the compost would receive uniform aeration. Preliminary experiments were conducted with placing perforated pipes through the center of the compost bulk. However, delivering air down through the center of the compost proved to be problematic and did not appear to distribute air to the compost effectively.

4.2.2. Temperature monitoring system

Four precision temperature sensors (LM 335, National Semiconductor Corporation, Santa Clara, CA) were placed in each barrel to provide a temperature profile of the entire volume of compost. Initial experiments using geometrically similar vessels proved that the difference in temperatures between the outer edges and the center at the same vertical level were insignificant, and consequently, the sensors for each vessel were located on the vertical center-line at different heights (Figure 5.2). This minimum horizontal temperature differential is also supported by Hogan *et al.* (1989) who reported finding only small horizontal conductive fluxes in operating similar laboratory-scale reactors.

In each vessel, the sensors were securely fastened to a steel rod 5 mm in diameter and 635 mm in length at intervals ranging from 125 mm to 175 mm. The intervals were governed by positions of sample bags containing compost and placed at a various depths to monitor bacterial counts, moisture content and dry bulk density in an associated experiment (Janzen *et al.*, in preparation.a). The rods, with the sensors, were pushed vertically through the middle of the compost at the center of the barrel to equal heights for all the vessels. Leads from each vessel's group of sensors were connected to an external circuit board that multiplexed the analog signal to an analog-to-digital (A/D) converter. Prior to use, all 24 temperature sensors were individually calibrated in a temperature-controlled water bath. The linear calibration equations derived from calibrations were used in a computer program to translate the digital voltage values into corresponding temperatures in degrees Celsius.

4.2.3. Gas Sampling System

An oxygen analyzer, operating on the principle of the magnetic susceptibility of O_2 gas (540A Industrial Oxygen Analyzer, Taylor Servomex, Sussex, England), and an infrared (IR) carbon dioxide analyzer (Model 846, Beckman, Fullerton, CA) were used in measuring the concentrations of O_2 and CO_2 respectively. Both analyzers provided remote 0 to +5 volt DC outputs which were used in data acquistion and logging. Ammonia gas (NH_3) was measured by a selective-filter infrared analyzer with a 0.145 m cell (Miran 103, Foxboro Analytical, S. Norwalk, CT). The Miran 103 provided a remote 0 to +2 volt DC output. All three analyzers were regularly calibrated with zero and span gases. Dry ambient air, assuming 20.96% oxygen, was used in spanning the oxygen analyzer. The CO_2 and NH_3 analyzers were calibrated with cylinders of dry CO_2 gas at 2.10% and NH_3 gas at 0.148% respectively. Cylinders of nitrogen (N_2) were used for zeroing of all three of the instruments.

Gas samples were drawn through 6.4 mm OD flexible polyethylene tubing running from the head space of each vessel to a gas collection manifold. Solenoid valves (203X-3, Airmatic-Allied Inc., Wilmington, OH) on each of the sample lines in the collection manifold determined from which vessel gases were to be drawn. The six solenoid valves were operated through solid state relays under computer control. A seventh, manually-activated, solenoid valve was connected to the bottom of the manifold to allow for drainage in the case of condensation forming and collecting in the outlet of the manifold. A single outlet from the manifold connected to the three gas analyzers which were in parallel (Figure 4.3). Three aquarium pumps were placed after the manifold and prior to the analyzers to provide sufficient flow rate through each analyzer. One of the pumps was located on the main line immediately after the manifold, supplying sample gases to all three analyzers. The second pump was placed on the main line after the O_2 and CO_2 sample line and was used to maintain the flow rate to the ammonia analyzer and the third pump supplied sample gases to both the oxygen and the carbon dioxide analyzer. Rotameters with needle valves were placed in series with the ammonia and carbon dioxide analyzers to ensure the proper rate of air flow was being delivered. The oxygen analyzer was equipped with a built-in rotameter and control valve. Due to the lower range of the ammonia analyzer, the ammonia gas inlet line was diluted at a ratio of 5:1 by volume with ambient air that was passed through a filter of calcium sulphate ($CaSO_4$) to remove any NH_3. The dilution air was drawn in by a variable speed aquarium pump (Optima, Rolf C. Hagen Inc., Montreal, Quebec). Figure 4.3 shows the entire layout for the sampling of gases.

Initially, none of the six gas sample lines were insulated. However, due to high relative humidity values in the vessels' head spaces, condensation in the lines caused problems. The moisture in the sampled air would condense immediately upon exiting the vessels and collect in the lines. Freezing of condensate in the sample lines inside the coldroom restricted the flow of air to the analyzers. The ambient temperature vessels produced similar problems. Due to the small diameter of tubing used for the gas sampling lines and the size of water deposits, the matrix potential of the water was greater than the negative pressure induced by the pumps, causing the lines to plug. Increasing the diameter of the lines delayed but did not resolve the condensation problem.

Moisture in the air samples also affected the accuracy of gas concentration readings, and threatened to slowly decrease the proficiency of the gas analyzers over time. The Servomex oxygen analyzer measured the true volume percentage of oxygen in the sample being analyzed. Thus it was necessary to eliminate water vapor in the sample so that the percentage of oxygen by volume increased in proportion to the amount of water vapor lost (Sybron, 1984). This increase provided the correct volume percentage of oxygen being released by the compost. Moisture affected the CO_2 and NH_3 analyzers by absorbing infrared light, producing a false reading (Beckman, 1972). Also, water vapor had the potential to damage the gold-plated surface inside the sample cells meant to reflect and contain the IR light within the cell. By positioning a drying agent in series prior to the inlet of each instrument all moisture was retained by the agent and the analyzers were protected.

Indicating drierite, calcium sulfate ($CaSO_4$), was used in series with the CO_2 and O_2 analyzers to retain all the moisture in the sample air and protect the cells from deterioration. However typical drying agents in granular form, such as silica gel and indicating/nonindicating $CaSO_4$, reacted with the NH_3 and, therefore, could not be used in series with the ammonia analyzer. In initial efforts to strip moisture from the ammonia gas, sample air was bubbled through alkaline solutions prior to analysis, but this resulted in reactions with ammonia and no effective method of chemically eliminating moisture from the NH_3 line was found. Alternatively, it was discovered that by placing a single tube dryer (MD-070-12P, Perma Pure Inc., Toms River, NJ) in series with the NH_3 analyzer, a large percentage of the remaining moisture was removed without effecting the concentration of NH_3 in the air. The tube dryer created a concentration gradient in moisture between the sample gas and a dry air flowing in parallel to the gas, and seperated by a semi-permeable membrane. This forced moisture to diffuse to the dry air and retained the NH_3 within the sample gas.

In the final design, 1.5 L Erlenmeyer flasks were used as a condensers. The six flasks, one on each gas line placed prior to the gas manifold, were arranged in a cold water bath with a mean temperature of 10 °C. Lines connecting the vessels to the cold bath were lead through flexible electrical conduit wrapped with 26 $W \cdot m^{-1}$ heat tape and covered in a 40 mm layer of duct insulation ($R = 0.9\ m^2 \cdot {}^\circ C \cdot W^{-1}$). This provided sufficient energy to maintain an average temperature of 45 °C inside the lines. This also prevented condensation in the gas lines while creating a temperature gradient large enough to condense most of the moisture out of the air in the glass flasks.

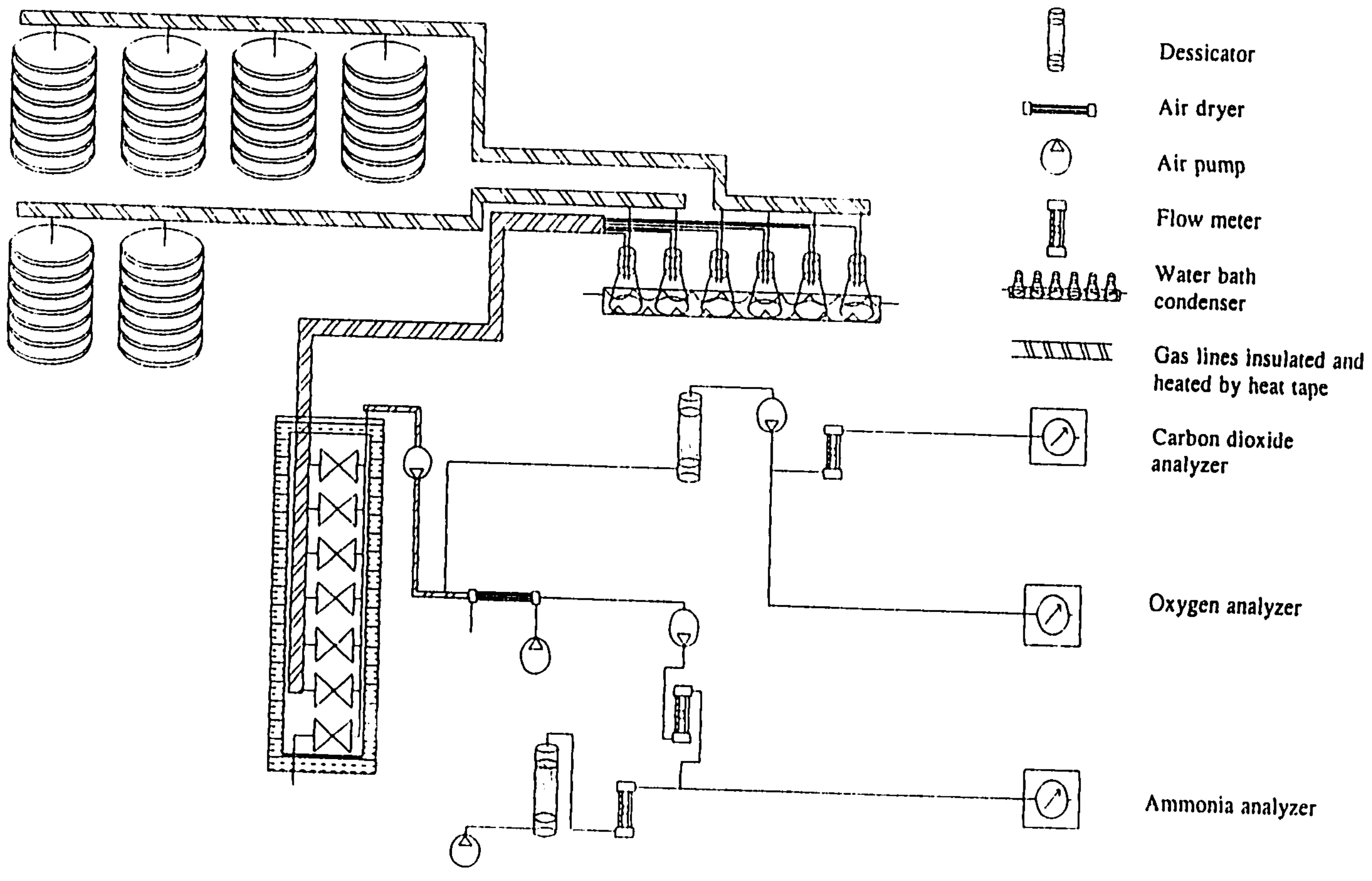

FIGURE 4.3 PHASE I GAS SAMPLING SYSTEM

Exposure of the gas to the water in the condensers allowed a percentage of the ammonia gas being produced to react with the water to become ammonium hydroxide (NH_4OH) (CRC. 1995). This ammonia was then unable to pass through the analyzer, resulting in an error in the measured value. However, amounts analyzed from previous experiments (Janzen, 1995, personal communication) were found to be negligible as a percentage of the total produced and could be ignored.

4.2.4. Data Acquisition and Control System

The entire system was controlled by software written in QBASIC running on a 80286/DX PC computer. A 12-bit data acquisition and control board (LC1600-P, Industrial Computer Source, San Diego, CA) was installed into the computer and created the interface between the computer and the operating and monitoring systems. The interface board was equipped with eight differential or 16 single-ended analog inputs and 32 bits of digital I/O. Since a total of 28 analog signals needed to be received, it was necessary to multiplex the inputs. The 24 analog signals produced by the temperature sensors were divided among three analog multiplexers (DG509A, Siliconix Incorporated,) where each multiplexer required four digital control lines. Four analog input lines were also set up to receive signals from the coldroom temperature sensor and the three gas analyzers. The operation of the fans, solenoid valves and one of the pumps was through digitally-controlled solid state relays (PS2401, CP Clare Corporation, Beverly, MA). The digital signals assigned to the sample gas solenoid valves were multiplexed to reduce the total number of digital lines required, while all other operations were controlled directly. All analog and digital multiplexers, along with the solid state relays, were contained in the circuit control box shown in Figure 4.1. An array of light emitting diodes (LED's) on the front of the box indicated which multiplexers, solenoid valves and fans were operating at any time. A single LED also indicated whether the circuit was receiving power.

4.3. Experimental procedure

The compost mixture used was made up of a 3:1 ratio (by weight) of raw dairy manure and barley straw. The barley straw was chopped to approximately 50 mm lengths and placed together with the manure in a 1 m^3 motorized mortar mixer. The ratio of straw to manure was calculated to give a carbon:nitrogen ratio of 40:1 with a moisture content of 60%. Approximately 40.8 kg of manure and 13.6 kg of straw were placed in each vessel. After being filled, vessels three to six were placed in the coldroom and one and two in the ambient environment. Temperature sensors were inserted into the compost of every vessel and gas lines run into the corresponding head spaces.

Four vessels (numbers three to six) were placed into a coldroom. Two of these vessels (numbers five and six, referred to as cold-cold) were ventilated with surrounding coldroom air and the other two (numbers three and four, referred to as warm-cold) with ambient air. The remaining pair from the six vessels (numbers one and two, referred to as warm-warm) were located outside the coldroom and were ventilated continuously at a rate of 3 $L{\cdot}min^{-1}$ with ambient air.

Initially, and after every successive mixing of the compost, the coldroom was set to room temperature allowing the mixture to begin composting. The coldroom temperature was turned down to -20 °C when vessels three through six had reached an average temperature of 55 °C (thermophilic conditions). The coldroom containing vessels three to six could attain mean maximum and minimum temperatures of 16.2 °C and -19.5 °C, respectively.

Imitating the Rutgers Process, software allowed the high volume fans supplying the 30 $L{\cdot}min^{-1}$ of air to engage individually at a specific maximum control temperature. In most cases this temperature was set at 55 °C although a much higher maximum temperature could be achieved in the compost. The fans supplying ambient air to vessels three and four through insulated lines were also set to activate if the average temperature in the vessels decreased below a specific minimum control temperature. This minimum temperature could be set at any time in the software, but was kept at 0 °C throughout the entire experiment. This control feature was never applied, however, as vessels were withdrawn from the coldroom if mean compost temperatures were less than 10°C.

The gas analyzers were spanned and zeroed with the proper gases at the end of each heating cycle during the entire experiment. Valves on both the 3 $L \cdot min^{-1}$ and the 30 $L \cdot min^{-1}$ air lines were also calibrated regularly to ensure proper rates of air flow to the compost.

Compost and coldroom temperatures were continuously read at 20 second intervals and displayed on a computer monitor. Temperature data were averaged and the value stored to file at intervals that could be changed at any time during a run. These intervals were usually set at one hour. Gas concentrations were only read and written to file prior to the closing of one solenoid valve and the opening of the next. The length of time between switching sample gas lines could be altered in the software at any point during the run but was normally kept at thirty minutes to allow sufficient time for all analyzers to stabilize. Although the concentration of each gas was also continuously displayed, the data were only updated on the screen when new readings were read in and stored to file. The software also recorded the hours elapsed between mixing and stored this value together with the temperature and the gas data. This accumulated value was continuously displayed on the monitor. Times of operation for each 30 $L \cdot min^{-1}$ fan were also monitored and stored.

Each vessel was disconnected and removed from the coldroom as the average vessel temperature approached freezing and there was no further evidence of microbial activity. When all the vessels in the coldroom had been retrieved, material from all six vessels was mixed individually in the mortar mixer, and the experiment repeated. Preliminary trials showed that mixing was required to re-start microbial activity after cooling and that an increase in the mean compost temperature was insufficient to reactivate degradation by itself.

4.4. Results

Temperature and gas concentration data were graphed for each vessel for two mixing cycles, each cycle lasting approximately 250 hours. Figures 4.4 and 4.5 show the average temperatures from the four sensors in each vessel for the first 500 hours of the experiment.

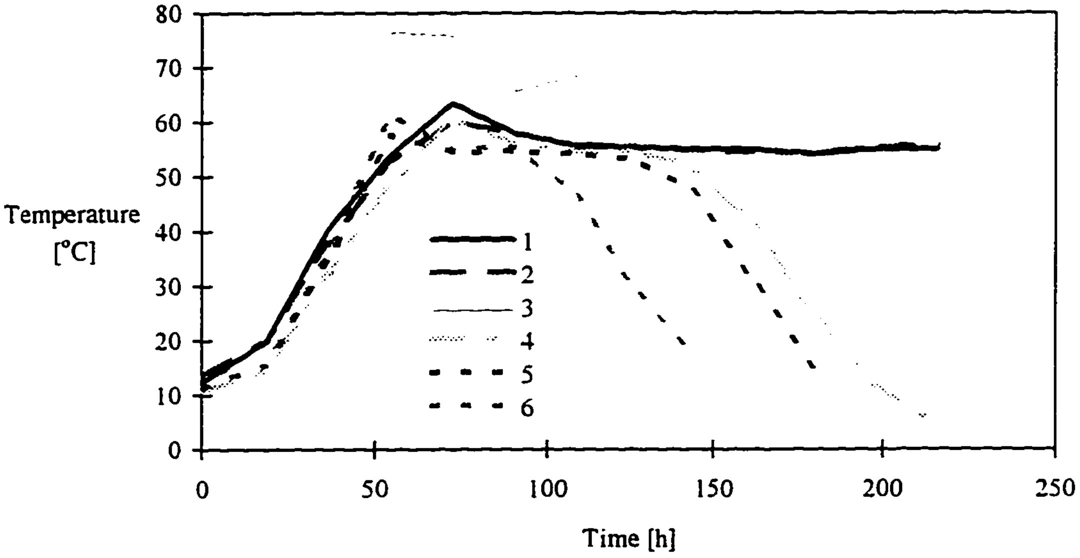

FIGURE 4.4 VESSEL TEMPERATURE FOR FIRST HEATING CYCLE

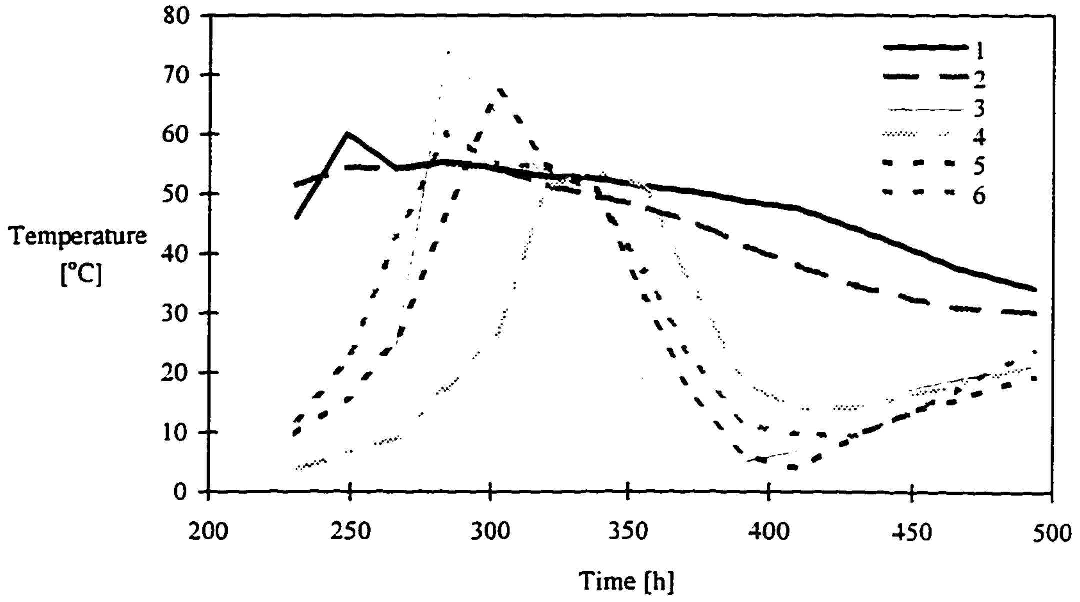

FIGURE 4.5 VESSEL TEMPERATURES FOR THE SECOND HEATING CYCLE

Graphs plotted from the gas concentration data are presented in Figures 4.6 to 4.8. These are also of the first 500 hours, or the two heating cycles. The first heating cycle or composting run lasted from 0 to 200 h. While the second heat cycle, after mixing of the substrate, was initiated at 237 h and monitored until 500 h when instrumentation and operations were shut down. The gas concentration data were converted to mass and are shown in the plots as cumulative values rather than instantaneous values. Rates of NH_3 and CO_2 production and O_2 consumption can be inferred from the slopes on the plots. Total mass of CO_2 produced and O_2 consumed for the three different treatments are shown in Table 4.1. Warm-warm vessels showed the greatest amounts of CO_2 evolved and O_2 produced for the duration of heating cycles. The respiratory quotient (RQ = no. mol CO_2 evolved/no. mol O_2 consumed) were calculated and tabulated also in Table 4.1. Numbers in parentheses in Table 4.1 are the standard deviations (n=2). The respiratory quotient was higher in warm-warm (0.970 ± 0.004) vessels than in warm-cold (0.901 ±0.017) and cold-cold (0.893 ±0.004) vessels.

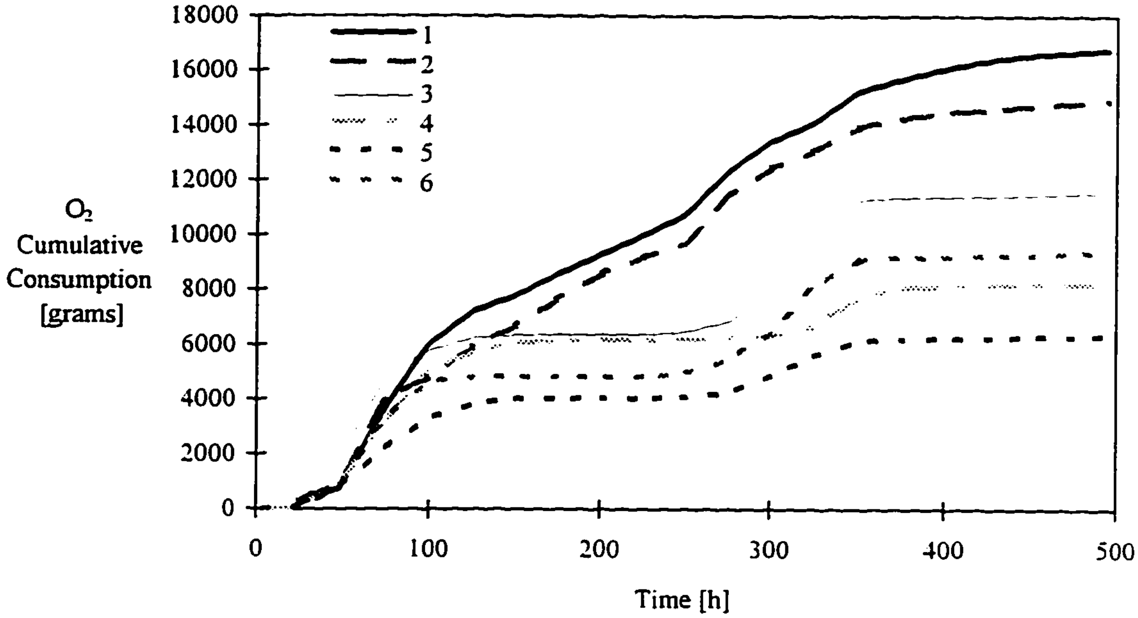

FIGURE 4.6 CUMULATIVE CONSUMPTION OF OXYGEN DURING TWO HEATING CYCLES

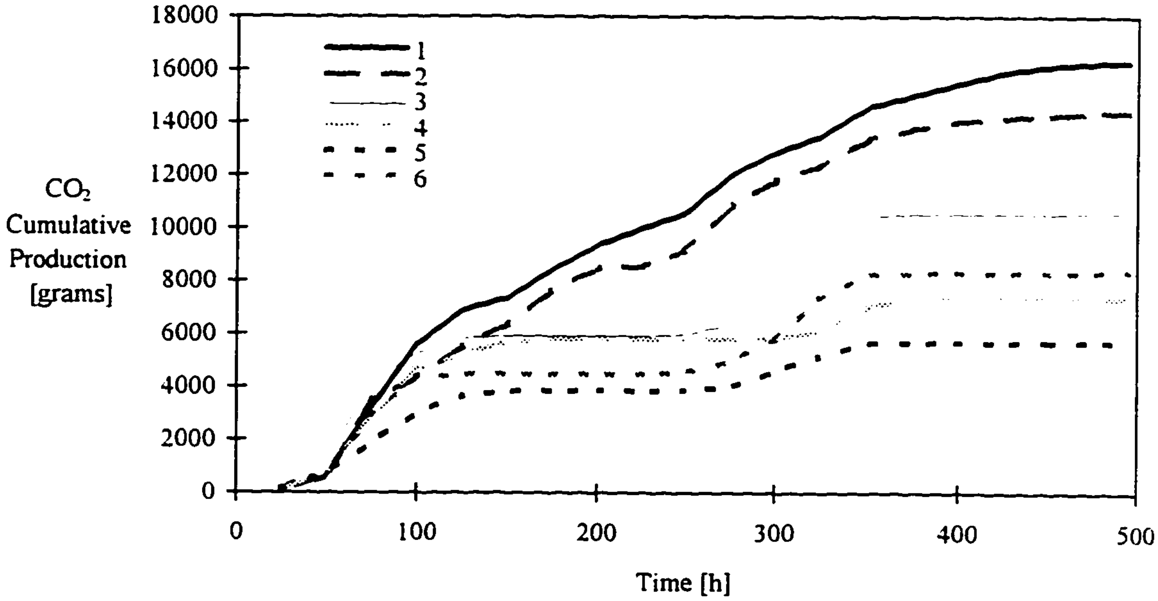

FIGURE 4.7 CUMULATIVE PRODUCTION OF CARBON DIOXIDE DURING TWO HEATING CYCLES

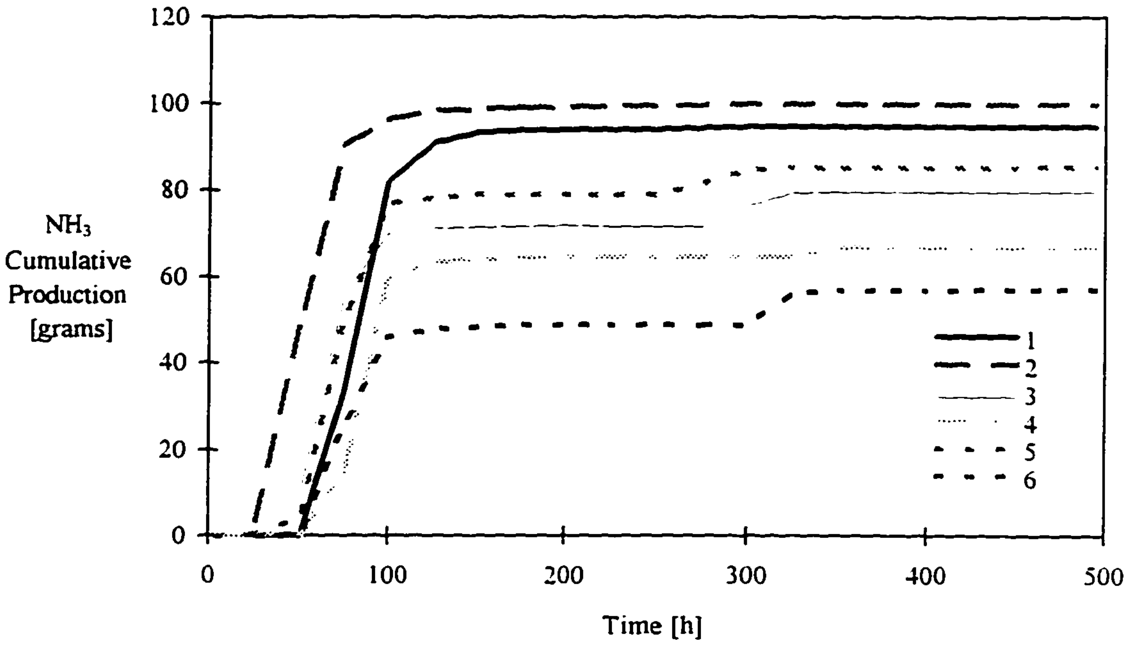

FIGURE 4.8 CUMULATIVE PRODUCTION OF AMMONIA DURING TWO HEATING CYCLES

TABLE 4.1 TOTAL EVOLUTION OF CO_2 AND O_2 CONSUMPTION IN 500H

Treatment	CO_2 evolved		O_2 consumed		RQ	
	g vessel^{-1}					
warm-warm	15361	(1340)	15834	(1319)	0.970	(0.004)
warm-cold	8966	(2280)	9933	(2344)	0.901	(0.017)
cold-cold	7037	(1895)	7884	(2161)	0.893	(0.004)

An average ambient temperature of 20 °C and a relative humidity of 30 % was recorded for the first 500 h of the Phase I experiment. This was the temperature of the ventilating air supplied continuously to the warm-warm vessels (numbers 1 and 2), the warm-cold vessels (numbers 3 and 4), and during the initial hours for the two heat cycles, to the cold-cold vessels (numbers 5 and 6). The coldroom was activated at 57 and 345 h for the first and second heating cycles respectively. The air in the coldroom was returned to ambient conditions at 216 h in the first heating cycle and at 416 h at the end of the second heating cycle. Air temperatures in the coldroom, when activated, fluctuated from -10 to -20 °C.

4.5. Discussion

4.5.1. Temperature

Temperature profiles in Figures 4.4 and 4.5 show that thermophilic conditions were reached in all six vessels within 30 h of the initiation of the experiment. This time frame is typical for composting with constant aeration (Sikora *et al.*, 1983). After the coldroom was initiated in both cycles, temperatures in vessels three to six decreased, while temperatures in vessels one and two remained constant. This indicated that the control composting systems for vessels one and two were operating as intended, as the cold air environment exhibited adverse effects on vessels three to six. Also, the temperature in the warm-cold and cold-cold vessels decreased more rapidly in the second heating cycle than in the first cycle. In the first cycle temperatures remained at 55°C for 50 to 75 h, but immediately decreased in the second cycle when the coldroom was initiated. The coldroom was active for 168 h for the first heating cycle, while only active for 70 h in the second. A possible reason for this decrease in time between cycles is because of a decrease in available carbon and nitrogen sources to provide sufficient activity to maintain thermophilic conditions. This is supported by the fact that no activity was noted after the temperature of the ambient air in the coldroom was increased to 20°C. Mixing of the composting material was required to expose different substrate and re-instigate activity.

In both heating cycles the warm-cold and cold-cold treatments show a very similar decrease in temperature. During the first heating cycle (Figure 4.4) however, the cold-cold treatments (vessels five and six) displayed an earlier decrease in temperature than the warm-cold treatments. While in the second cycle (Figure 4.5), one of the warm-cold treatments, vessel three, actually decreased in temperature earlier than the cold-cold vessels five and six. In both cases, little difference is seen between the warm-cold and cold-cold treatments, indicating that the temperature of the inlet air had little effect on the rate of activity of the microorganisms. This was counter to expectations for the warm-cold vessels as it was felt that the enthalpy of the warm inlet air would be sufficient to overcome conductive and evaporative cooling heat losses from the vessels. From this it can be concluded that the rate of heat loss, either through conduction or latent and sensible heat in the air, from vessels three and four was greater than the energy received in the ventilating air, plus the rate of heat generated.

Despite the fact that 80 to 90% of total heat is lost through the latent heat of evaporative cooling (MacGregor *et al.*, 1981), evaporative losses seemed to have played only a small role in the rapid loss of heat from vessels in the coldroom, three to six. This is supported by the small differences in the decrease in temperatures between the warm-cold and cold-cold treatments. Greater evaporative and sensible losses would have been expected from the cold-cold vessels during thermophilic conditions compared to the warm-cold vessels due to the amount of water vapor present in the cold inlet air. The moisture content in the ventilating air for the cold-cold vessels was less than that in the warm-cold vessels and, assuming that the temperature of the exhaust air equaled that of the compost, had a greater potential to take up greater amounts of moisture, and thus heat, from the composting masses.

The small differences between the warm-cold and cold-cold treatments indicated that conductive losses were the major mechanism of heat loss from all the vessels. A possible explanation for the temperature gradient similarities between the warm-cold and cold-cold treatments is that the vessels were inadequately insulated. Large amounts of heat could have been lost through the bottoms of the vessels as these were not insulated and the vessels stood directly on a concrete floor. This would have caused heat loss from the warm air in the plenums of vessels three and four so that the warm-cold treatment would have been very similar, in fact, to the cold-cold treatment.

The large conductive losses seen in the Phase I laboratory studies are supported by claims made by Hogan *et al.* (1989). These researchers concluded that because of large surface area to volume ratios in laboratory-scale composters, the majority of heat lost from the system is through conduction rather than convection. Or inversely, conductive heat losses from a large compost pile in a warm environment would be minimal and temperature control can be attained through the manipulation of ventilation (convective) rates. Translating this to large-scale composting in cold-climate conditions would result, however, in an increase in conduction due to the colder surroundings. This increase in conductive heat loss can be key to optimizing the composting process in colder environments. Typically, control in the composting process is achieved through proper ventilation rates providing adequate oxygen and heat removal through evaporative cooling (Nakasaki *et al.*, 1992; Sikora and Sowers, 1985; MacGregor *et al*, 1981). However, in cold climates the emphasis should be to ensure proper moisture and gas diffusion with reduced ventilation, and if required, focus on optimizing heat removal through conduction rather than convection. If gas diffusion becomes the limiting factor in cold climate composting, it would require the ventilation rate to be fast enough to ensure that the concentration of O_2 gas in the compost matrix to be greater than 10%. Concentrations of $O_2 < 10\%$ are limiting to proper microbial metabolism.

4.5.2. Moisture

Although moisture content was not recorded as debilitating during the Phase I study, it can be predicted that the water vapor within the compost matrix can play an important role in gas diffusion. Assuming the inlet air reaches thermophilic temperatures, the amount of water retained by the ventilating air will be inversely proportional to the temperature of the inlet air.

However, upon approaching the colder perimeter of the compost, the water vapor in the air would condense out, and form an outer frozen layer of substrate. This characteristic is typical in winter composting (Lynch and Cherry, 1996; Jongejan, 1980), and can debilitate proper respiratory gas exchange.

For uninhibited microbial respiration, O_2 concentrations no less than 5% are required (Willson *et al.*, 1980; Parr *et al.*, 1978). This low concentration was not detected in any of the vessels, but neither was gas transfer debilitated. Vessel walls and lids were insulated and exhaust ports heated. This, for the most part, deterred moisture from freezing at the perimeter of the compost and allowed gases to exhaust undetered. In the field, a frozen perimeter would become a resistive barrier for proper gas diffusion.

4.5.3. Gas analyses

The shapes of the curves for the cumulative CO_2 consumed and O_2 produced during both heating cycles are very similar (Figures 4.6 and 4.7). This was expected as CO_2 evolving from cell metabolism must reflect the amount of O_2 consumed for respiration. Each curve in both Figures 4.6 and 4.7 also related well to the temperature dynamics of the three treatments. Higher rates of CO_2 emission and O_2 consumption were achieved during periods when temperatures were at maximum values of 50 to 60°C. This has also been verified in studies by Jeris and Regan (1973), and Suler and Finstein (1977) who both report maximum CO_2 outputs between 55 and 60°C. Warm-warm vessels produced and consumed the greatest amounts of CO_2 and O_2, respectively, in comparison to the warm-cold and cold-cold vessels. Table 4.1 shows that higher rates of CO_2 evolved and O_2 consumed were also evident in the warm-cold vessels in comparison to the cold-cold vessels. Also from Table 4.1, warm-warm vessels produced the highest respiratory quotient (*RQ*) value while warm-cold vessels had a higher RQ value than cold-cold vessels. This again suggests that gas exchange can play an important role as an operational parameter while composting in colder environments.

The varying values of RQ between treatments are consistent with those reported by Nakaski *et al.* (1985) and Nakaski *et al.* (1987) where an increase in RQ values was reported to be directly proportional to an increase in temperature. These authors suggested that, at higher temperatures, catabolic activity would increase and potentially create anaerobic zones inside the composting matrix. This anaerobiosis would support catabolism through fermentative decomposition and anaerobic respiration (Nakasaki *et al.*, 1992).

The increase in RQ and, therefore, suggested catabolic enhancement would result in an increase in free carbon released as CO_2 gas. This, however, would suggest an increase in the mineralization of nitrogen and allow for more N to be released during composting at higher temperatures (Janzen *et al.*, in preparation, b). Nakasaki *et al.*, (1985) proposed that the high temperature composting would be dominated by catabolism and therefore increase NH_3 emmisions. This explains the higher releases of NH_3 gas during peak temperatures in the warm-warm vessels as opposed to the warm-cold and cold-cold vessels. However, data conflicts with this as well, as NH_3 evolution declined after 100 h and 325 h for the first and second heating cycles respectively, despite temperatures remaining unchanged in most vessels. This is clearly shown in the warm-warm vessels in both cycles where temperatures were maintained at 55 °C, yet no further NH_3 gas was released. Although reports have been made that claim NH_3 release to be strongly temperature-dependent (Ross and Harris, 1982; Burrows, 1951), recent work suggests temperature does not have a significant effect on cumulative NH_3 loss (Jackson and Line, 1997). Results from all three treatments tend to support this latter claim. The release of NH_3 was negligible in the warm-warm vessels at the start of the second heating cycle although the compost attained temperatures of 50 to 60°C. An increase in effective C:N ratio is one hypothesis proposed to explain the NH_3 emmission pattern (Janzen *et al.*, in preparation, b). However, this cannot be validated in this case as C:N ratios were not measured for the three treatments. Janzen *et al.*, (in preparation, b) suggests that NH_3 evolution coincides with increased ventilation rates due to an increase in ammonification. This would explain the peak NH_3 emmisions, as ventilation rates were temperature-dependent in all vessels.

The surge of NH_3 evolution can also be hypothesized to be contributed by a limited quantity of soluble nitrogenous compounds initially available in the compost material. During the on-set of rising temperatures, catabolism can out-weight anabolism, causing the nonrenewable N resource to mineralize and allow ammonification to occur. Ammonification will increase the pH and, at values greater than 8.5, nitrogen will occur in the form of free ammonia rather than ammonium ion (NH_4^+)(Koster, 1986). Although pH was not recorded, a slight rise in pH is typical during the initial rise in temperature. As the composting process in the warm-cold and cold-cold vessels was interrupted by a change in ambient and ventilating temperatures, small concentrations of soluble nitrogenous compounds were still available and later exposed to bacteria during mixing at the end of the first heating cycle. This would explain the small surges in NH_3 evolution in the warm-cold and cold-cold vessels at the start of the second heating cycle as opposed to the very small amounts released from the warm-warm vessels.

4.6. Phase I Conclusion

The results collected during both heating cycles in the Phase I study provided sufficient evidence towards the proper roles of several composting parameters in cold climate composting.

Typically, control in the composting process is achieved through proper ventilation rates providing adequate oxygen and heat removal through evaporative cooling (Nakasaki *et al.*, 1991; Sikora and Sowers, 1985; MacGregor *et al*, 1981). However, the data collected from the large vessels proves the more logical suggestion for cold-climate composting practices; that a control variable is not required, but rather operational parameters need to be considered.

The temperature profiles for the composting vessels suggest that the flux in conductive losses would be large enough to eliminate evaporative cooling and sensible heat loss as a control function in cold-climate composting. Rather, microbial respiration, as related in the supply of oxygen and transfer of carbon dioxide, can be assumed to be one of the most important operational parameters effecting composting in colder environments.

Sources of N in the cold-warm and cold-cold vessels did not appear to play a limiting role. Whether this is applicable to large-scale winter composting operations is not certain, as the exact nature of N dynamics during composting is undecided.

Data obtained and analyzed from the Phase I study led to the conclusion that a more focused study was needed to further analyze the effects of low temperatures on the rate of microbial activities. A heat balance was required to properly define all the involved mechanisms of heat flow. To achieve this, a more focused and controlled composting system was needed.

4.7. Phase I Recommendations

The objective of Phase I was to gain an understanding of the dynamics of cold-climate composting. However, to ensure effects of low aeration temperatures were properly measured, it was necessary to be able to develop a heat balance describing the dynamics and kinetics of the composting process. The composters used in the Phase I study were not designed to allow for the measurement of conductive and convective heat losses, thereby making it impossible to gain a complete quantitative understanding of the effects on microbial activity of low temperatures. A composter system was required that allowed for the control and analysis of each individual mechanism of heat transfer, thereby accounting for all areas of thermal energy loss. To achieve this, a more defining composting reactor was needed to maintain greater control over heat loss, air flow temperature and rate, and compost homogeneity.

5. Phase II - Bench-scale Cold Climate Composting

5.1. Experimental Design

Six bench-scale bioreactors were designed so that there would be a negligible temperature gradient between the compost material and its surroundings. This would reduce conductive heat losses to negligible levels and simulate compost within a large mass of material.

A number of preliminary runs (R1-R7) were carrried out in the bench-scale composters, prior to the cold-climate experiment, to verify that the system could provide and maintain thermophilic conditions for the compost. Repeatability in the rate of composting, measured via compost temperature, CO_2 and NH_3 evolution, and O_2 consumption during experimental runs, also needed to be obtained. The final preliminary runs (R6 and R7) will be reported here. After these were done, a completely randomized experiment was set up and carried out to test the hypothesis that low ventilating temperatures would have an effect on thermogenesis in compost exhibiting thermophilic activity (reported as R8). Three different treatments were applied to the six bench-scale composters with each treatment done in duplicate. The treatments consisted of continuously ventilated air at ambient temperatures (20°C) in vessels one and three, at 5°C in vessels two and four, and at -5°C in vessels five and six. Compost, water bath, and ventilating air temperatures, as well as O_2 consumption, CO_2 and NH_3 production were continously measured, monitored and recorded. Initial and final moisture contents and masses were also recorded.

Total heat output and rate of heat production were determined based on the enthalpy (heat content) differential between the inlet and exhaust air.

5.2. Materials and Methods

The layout of the entire system for Phase II of the cold-climate studies is shown in Figure 5.1. Each component of the system in Figure 5.1 is described below.

5.2.1. Bench-scale bioreactors and water bath.

A detailed drawing of a bioreactor submerged in a water bath is given in Figure 5.2. The main bodies of four of the bioreactors were constructed with clear acrylic pipe while two were made with white PVC pipe. Both types of vessels were approximately 203mm ID with 6mm thick walls. The total depth, including the aeration plenum, of each reactor was 330mm, creating 9.0 L of space for composting and a 1.15 L aeration plenum in each vessel. The floors and lids were made of 6mm-thick clear acrylic plastic. Lids were screwed to a mounting flange with eight, equally spaced bolts. To prevent water from the water bath entering the composter via the lid, grooves were machined in the flanges and lids to fit a 203mm diameter O-ring, creating a seal between the water and the compost. In addition, 25mm thick polystyrene insulation ($R=0.88\ m^2 \cdot K \cdot W^{-1}$) was glued onto the bottom and inner walls of the aeration plenums at the bottom of the vessels. This prevented heat flow from the heated water bath to the plenum, which could affect the temperature of the aeration air. Protruding through the centers of each of the lids were two 13mm ID PVC pipes long enough to clear the water levels of the water baths. One of the pipes acted as the exhaust air outlet while the other contained wiring leading to a temperature sensor that was located near the center of the vessel.

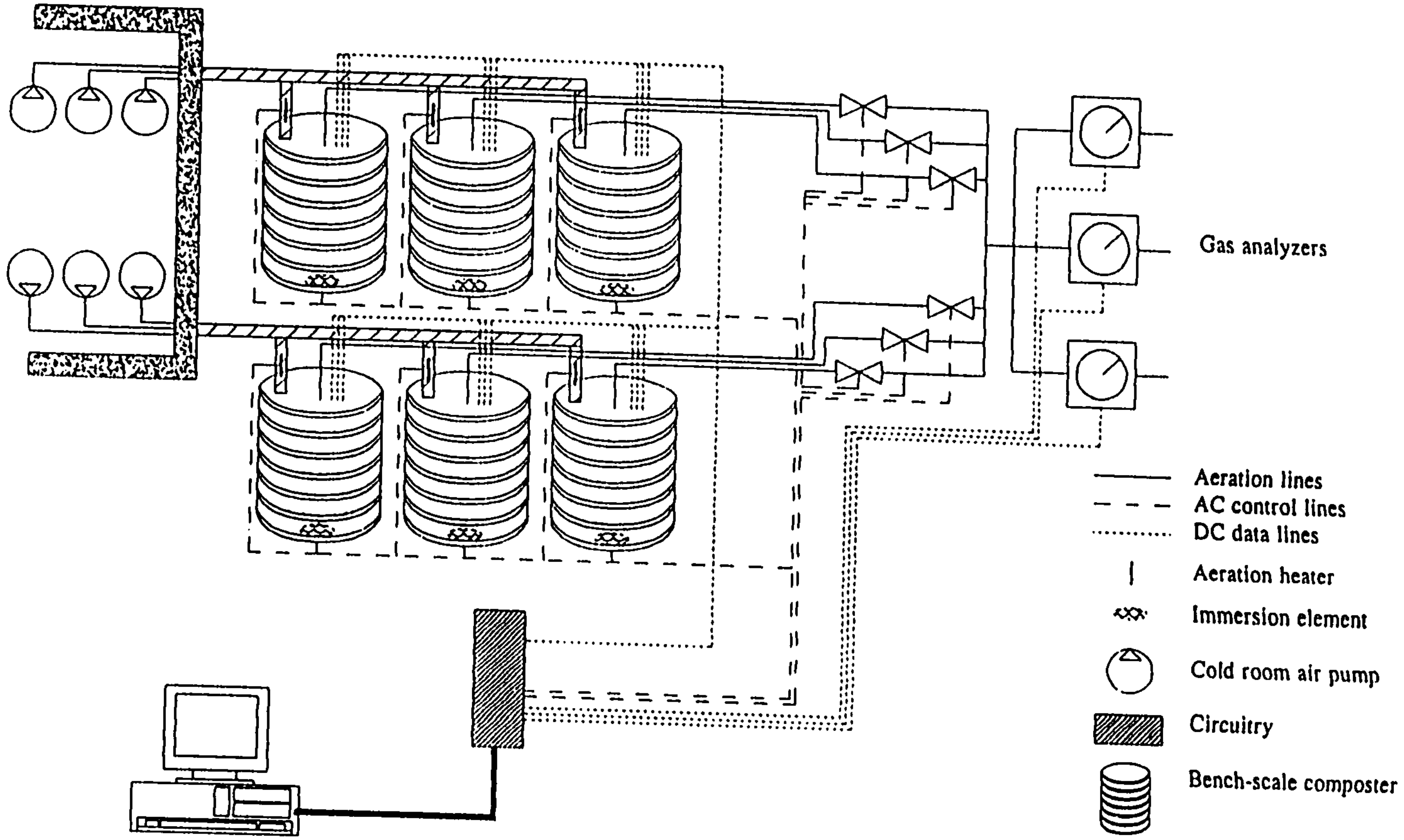

FIGURE 5.1 PHASE II COMPOSTING SYSTEM

Each compost vessel was submerged in a 60 L heated water bath. The temperatures of the water baths were controlled by a computer through feedback from temperature sensors located in the water bath. The computer actuated a 1500 W immersion element (39-301TM, Glen Gerry Industries, Toronto, ON) if the temperature of the compost exceeded the temperature of the water in the water bath by 0.5°C. The heating element was deactivated if the temperature of the water surrounding the composter was within 0.3 °C of the compost temperature. This temperature control range was deemed acurate enough to minimize conductive heat fluxes between the compost and water bath (Figure 3.1). As well, the temperature sensors were accurate only to ± 0.5°C (National Semiconductor Corporation, 1990) and greater precision could not have been achieved. Sikora *et al.*, (1983) used a similar water bath and composter temperature control stratagy. Water in each water bath was circulated continuously by submersible aquarium pumps (MaxiJet, Aquarium Systems, Mentor, OH).

Each vessel was kept submerged in the water bath by a frame made up of 6.3mm by 25.4mm flat steel bar and 6.3mm diameter threaded rod. The design can be seen in the cross sectional drawing in Figure 5.2.

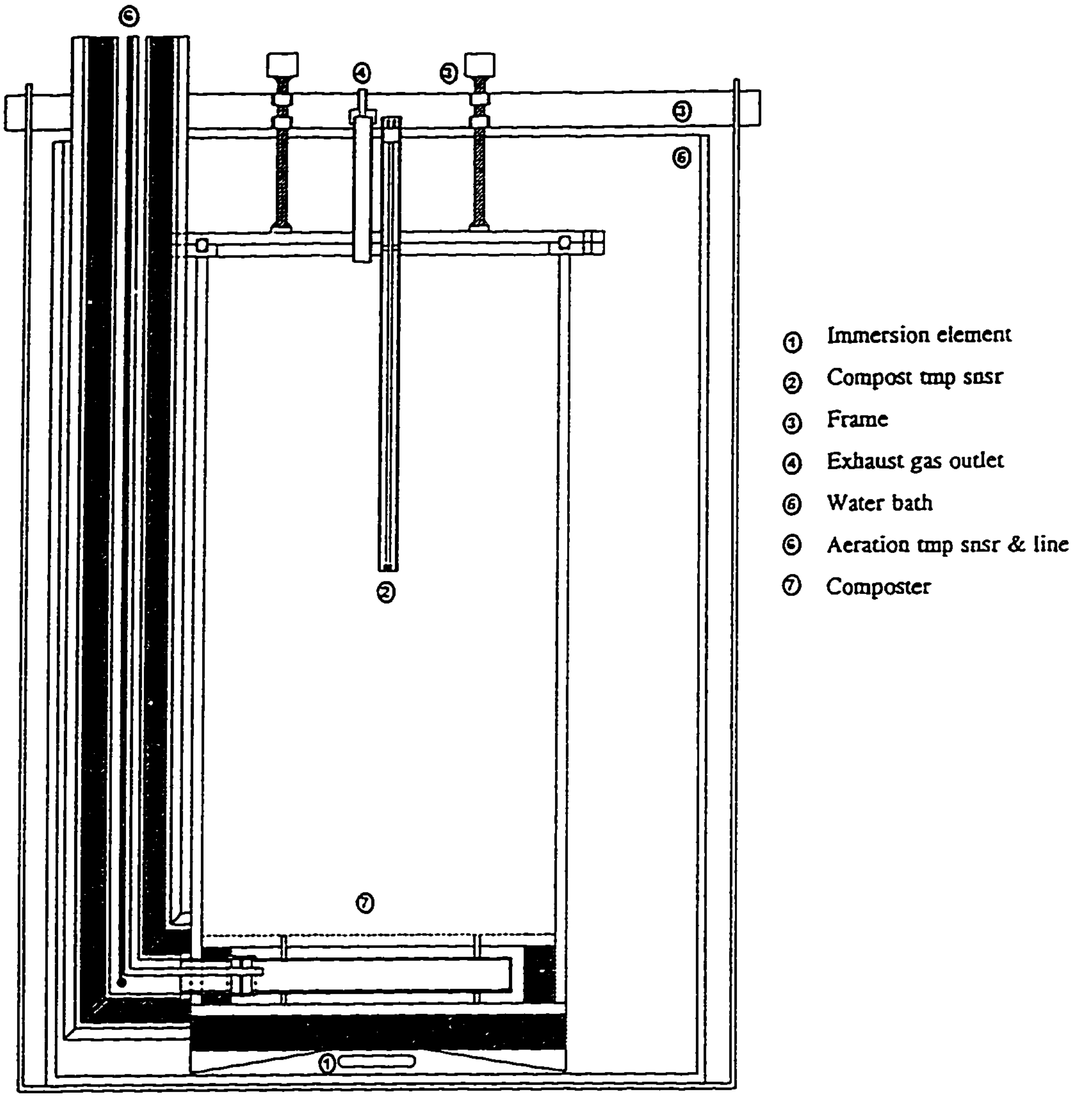

FIGURE 5.2 PHASE II BENCH-SCALE COMPOSTER

5.2.2. Ventilation system

Ventilation was supplied via 6.4mm OD polyethylene tubing and was introduced through the side near the bottom of each vessel. The 6.4mm tubing discharged into a larger, 22mm OD, perforated PVC pipe located on the diameter of the vessel near the bottom of the 1.15 L plenum (Figure 5.3). This plenum, constructed by supporting a 0.79mm-thick, perforated, stainless steel sheet approximately 38 mm from the vessel floor, was designed to allow air to flow uniformly up through the compost matrix.

During the cold-climate experiment (R8), the lowest temperature of the ventilating air required to be introduced into the compost was -5°C. Each air line however, passed through the water bath which attained maximum temperatures of 70°C. Furthermore, the ventilating air for each treatment was pumped from a temperature-controlled coldroom that could only achieve a minimum of -20°C. These specifications allowed for a 15°C change in temperature in the ventilating air between the coldroom and the plenum of the composter. This required the ventilating air line to be properly and thoroughly insulated to prevent any heat flows from the water bath and ambient from increasing the temperature of the ventilating air. This was achieved by pumping large volumes of air from the coldroom along the outside of the 6.4mm aeration tubing which ran inside a 38.1mm PVC pipe connecting each plenum with the outlet of the coldroom. Two large fans were used to deliver the high volume flow rates: a 152.4mm centrifugal fan driven by a 120V, 372.8W motor operating at 1550 rpm, and a 120V, 372.8W motor driving a 304.8mm vane fan (No. 9, Cincinnatti Fan & Ventilator, Cincinnatti, OH) operating at 3450 rpm. The 38.1mm pipe, housing the ventilation line, was also insulated on the outside with 15mm of foil-backed fiberglass pipe insulation ($R=0.41\ m^2 \cdot K \cdot W^{-1}$). The high volume air flow acted as insulation and prevented the ventilating air from gaining heat and thus increasing in temperature. Four 6.35mm holes were drilled in the 38.1mm pipe near the water bath allowing for the high volume insulating air to exit. Prior to entering the water bath. the insulated pipe containing the ventilation line ran inside a 76mm ID ABS pipe attached to the composter and connected to the plenum inlet at the bottom the of the composter.

In case the temperature of the ventilating air needed to be increased, the air line was coiled several times around a computer-actuated heating coil before entering the composter. At this point 6.4mm OD copper tubing was used in place of the polyethylene line. The temperature of the aeration air was compared to a preset value by the computer and the heater core was activated or deactivated accordingly. Details of the ventilation system for each of the bench-scale composters are shown in Figure 5.2.

Air was supplied continuously at rates of 0.5 to 3 $L\cdot min^{-1}$ from the coldroom by varying sizes of aquarium air pumps (Rolf C. Hagen Inc., Montreal, PQ) located in the coldroom. Additional flow control was provided by needle valves on the outlets of each vessel (section 5.2.4).

To allow the vessels to be removed from the water baths for mixing and weighing. the inlet and outlet air lines could be disconnected from the vessels. The inlet air line could be disconnected after the air heater and prior to entering the water bath, while the exhaust line could be disconnected from the exhaust port on the lid of the vessel.

5.2.3. Temperature monitoring

Three temperature sensors (LM335H, National Semiconductor Corporation, Santa Clara, CA) were used to measure the temperature of compost, ventilation air, and water bath of each unit. The sensor used to measure compost temperature was located 140mm beneath the lid in the center of the composter while the aeration sensor was located in the 38.1mm PVC pipe along side the ventilation line at the inlet into the plenum at the bottom of the composter. Preliminary tests confirmed that the temperature of the high volume insulating air from the coldroom was the same as that of the air flowing in parallel inside the 6.4 mm ventilation line. The water bath sensor was fastened to the end of a 400 mm steel rod that hung vertically from the edge of the water jacket. Coldroom and ambient temperatures were also measured. thereby totalling 20 analog temperature signals for the complete six-vessel system.

Prior to installation, all sensors were individually calibrated using a temperature-controlled water bath. The calibration equations were entered into the control software and were used to translate the digital voltage values provided by the sensors into corresponding temperatures in degrees Celsius. All temperature sensors were re-calibrated after every two experimental runs.

5.2.4. Exhaust gas control and analysis

A schematic of the exhaust gas sampling system is shown Figure 5.3.

An oxygen analyzer (540A Industrial Oxygen Analyzer. Taylor Servomex. Sussex. England). operating on the principle of the volume magnetic susceptibility of O_2 gas (Sybron. 1984). was used in determining the concentration of oxygen. An ammonia analyzer (Model 880 Beckman. Fullerton. CA) and a carbon dioxide analyzer (Model 846, Beckman. Fullerton. CA) both measured respective gas concentrations using infra-red absorption. All three of the analyzers had remote 0 to +5 V_{DC} outputs which were used in transferring data to the data-acquisition computer.

All three analyzers were calibrated before each experimental run with zero and span gases. In spanning the O_2 analyzer, dry ambient air was used. assuming 20.96% oxygen (Mayhew and Rogers. 1977). The NH_3 and CO_2 analyzers were calibrated with certified gas mixtures containing 0.148% dry NH_3 gas and 3.98% dry CO_2 gas respectively. Pure nitrogen (N_2) gas was used to zero all three analyzers.

Exhaust gases from the composters were delivered to the three gas analyzers through 6.4 mm OD polyethylene tubing. Due to high relative humidities in the exhaust gases, each sample gas was run through two condensers prior to entering the instruments. A 30 ml plastic container was placed in series with the sample line at the exit of each vessel to trap initial condensate formed due to the temperature gradient between the exhaust gas and ambient conditions. The second condenser in each sample line provided an adequate temperature differential to condense the remaining moisture in each sample gas. These condensers each consisted of a 1.5 L Erlenmeyer flask placed in a 20 L cold water bath with a continuous circulated supply of cold water at ≤10 °C. Exposure of the gas to the condensate allowed a percentage of the NH_3 gas being produced to react with the water to become ammonium hydroxide (NH_4OH) (CRC, 1995). However, amounts analyzed from previous experiments (Janzen, 1995, personal communication) were found to be negligible as a percentage of the total produced and could be ignored. Concentrations of O_2 and CO_2 gas were unaffected by the condensate.

Following the condenser on each line was a rotameter with an in-line needle valve (FL4213-V,Omega, Laval, PQ). These were adjusted manually to ensure that correct rates of flow were being pumped through the composters.

Air passing through the rotameters was discharged into a gas collector manifold. This incorporated seven, three-way, universal solenoid valves (U8320B3, Ascolectric Limited, Brantford, ON) which were actuated individually by a computer through relays. Six of these were used in selecting from which vessel gases were to be drawn, while the seventh was used to purge the gas analyzers with ambient air after gases from the sixth vessel had been monitored. An aquarium air pump (Optima, Rolf C. Hagen Inc., Montreal, PQ) was connected to the seventh solenoid valve and provided the flow to purge the instruments. When deactivated, the solenoid valves were open to atmosphere allowing vessels to vent to atmosphere.

A single, uninsulated gas line emerged from the manifold and connected to the end of a 25.4mm PVC pipe, 254mm in length, that contained flow straightening vanes near the downstream end. A hot wire anemometer probe (Velocicalc, Model 8350, TSI Incorporated, St. Paul, MN) inserted through a 6.35mm hole at the far end of the pipe and mounted perpendicular to the pipe, served to measure exhaust gas flow rates. The anemometer was able to relay flow rates to the computer through a RS-232 serial port. Flow rates were matched with the corresponding composter by the computer according to which valve was activated at the time the measurement was taken. These values were then stored. Flow rates of exhaust gases from each composter were continuously monitored but only read by the computer several seconds before switching valves.

After the flow measuring device, the single, uninsulated gas line divided into two lines. One of the lines directed gas into the ammonia analyzer, and the other line split to direct gases to the oxygen and carbon dioxide analyzers.

Because moisture in the air samples affected the accuracy of readings and threatened to slowly decrease the performance of the gas analyzers over time (Leonard *et al.*, 1996), a dessicator filled with calcium sulphate ($CaSO_4$) was situated in series with the carbon dioxide and oxygen analyzers to retain any remaining moisture in the sample air. The O_2 analyzer measured the true volume percentage of O_2 in the gas being analyzed. Thus, it was necessary to eliminate water vapor in the sample gas so that the percentage of O_2 by volume increased in proportion to the amount of water vapor removed (Sybron, 1984). This proportional increase allowed for the correct volume percentage of O_2 being released from the compost to be measured. Moisture could affect the CO_2 and NH_3 analyzers by absorbing infrared light, resulting in a false reading (Beckman, 1972). Water vapor also had the potential of damaging the gold plating on the inside surfaces of the sample cells. By placing a drying agent in series with the analyzer inlet, any remaining moisture would be stripped from the sample gas thereby protecting the instrument. This drying agent could not be used before the ammonia analyzer because of reactions between NH_3 and granular drying agents, such as silica gel and calcium sulphate.

The tube dryer used to filter moisture from the sample gas prior to the NH_3 analyzer in Phase I was no longer available and was therefore not used in the Phase II study. As well, due to the two condensers placed in series to the gas analyzers, the tube dryer was not required.

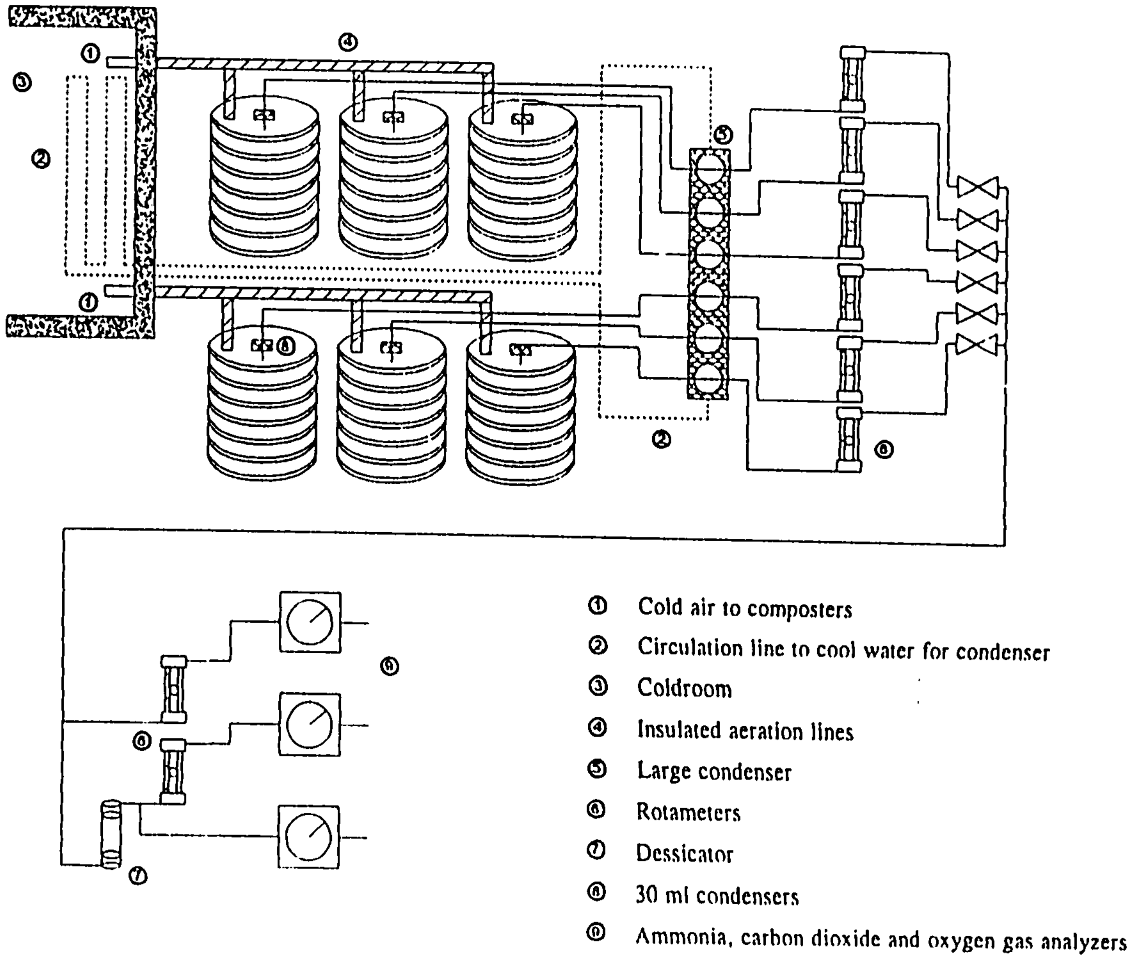

FIGURE 5.3 PHASE II GAS SAMPLING SYSTEM

5.2.5. Data acquisition and AC control system

Data acquisition and relay control were operated through software written in Qbasic running on a 80286/DX PC computer installed with a 12 bit analog to digital (A/D) converter board (DAS1201, Keithley Data Acquisition - Keithley MetraByte/Asyst, Taunton, MA) and a high speed serial card (HSP-1P, Logicode Technology, Inc., Camarillo, CA). The A/D board, controlled by software, created the interface between the computer and the instrumentation (except the anemometer) and control hardware. Although the A/D interface board was equipped with 16 single-ended or eight differential analog input lines, only three were utilized. The 23 analog signals produced by the 20 temperature sensors and three gas analyzers were reduced to three analog signals through three, digitally controlled CMOS analog multiplexers (74HC4051N, Motorola, Vancouver, BC). The serial board, also controlled through software, was used to communicate with the hot-wire anemometer to transfer flow rate data to the computer.

Temperatures and gas concentration data were continuously displayed and refreshed on the monitor and stored on the computer's hard drive at regular, predefined intervals.

Of the 24 digital input/output (I/O) channels on the A/D board, twenty were allocated to digital output control. The operation of 20 AC devices[2] (seven three-way solenoids, six aeration heaters, one aeration pump, and six water bath immersion elements) through digital control was achieved by using 14 digital lines, three 1-of-16 digital CMOS demultiplexers (74HC154N, Motorola, Vancouver, BC), and six CMOS quad R-S latches (MC14043B, Motorola, Vancouver, BC). The seven three-way solenoids, and one aeration pump were

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[2] Initially the AC control system was designed to control the six ventilation air pumps. This was later changed to allow computer control of the seventh solenoid valve and purging pump. The six ventilation air pumps were operated continously during each experiment.

actuated directly by eight, individually-controlled AC solid state switching relays (PD2401, CP Claire Corp., Chicago, IL) with a maximum rated load current of 1.0 A. The aeration heaters and the water bath heaters had higher power requirements and were actuated by individually-controlled AC solid state switching relays which in turn activated AC mechanical relays with a maximum load current rating of 15 Amps.

The mechanical relays were contained in an AC power unit while the solid state relays and remaining electronic components were built into a control circuit box. Both of these units are shown in Fig. 5.1. An array of light emitting diodes (LED's) on the front panel of the control circuit box indicated which control mechanisms were operating. A small toggle switch also on the front panel could switch off the AC power to the entire system, leaving the computer still operating and receiving and storing data.

5.3. Experimental procedure

The compost mixture used was made up of a 3:1 ratio (by weight) of raw dairy manure and barley straw. This 3:1 ratio provided a C to N ratio ranging from 42:1 to 47:1 with a moisture content of about 78%. The barley straw was chopped to approximately 50mm lengths when added and mixed with the manure. At the start of the experiment, approximately nine kilograms of manure and three kilograms of straw were mixed together in a 0.75 m^3 motorized mortar mixer. A small sample was taked from the mixed material to sample for moisture content, total nitrogen, total soluble carbon, total carbon, organic matter content, and ash content. The mixed straw and manure was then divided into six portions. Each portion was weighed and recorded individually, and the six composters filled. Portions ranged from 2.3 kg to 2.7 kg depending on the experimental run. Differences amongst wet masses in all six composters for the three trials reported were found to be not significantly different ($p > 0.05$). Each composter was then placed inside its water bath, coldroom aeration lines and temperature sensors were connected, water baths were filled to the top with water, and the data acquisition and control program was initiated.

Experimental procedures for studies aimed to verify the contol system and repeatabiliy of the composters (R6 and R7), required the temperature of the ventilation air to remain at 20°C. Therefore, although air was drawn from the coldroom, the coldroom was not activated and remained at ambient conditions. For the experiment conducted to test the hypothesis of adverse effects of low temperature ventilation on thermophilic composting (R8), the coldroom was actuated and set to provide air temperatures of -20°C. This was not initiated however until all six composters had reached thermophilic conditions. Temperatures within the coldroom remained at ambient conditions prior to this requirement. Once the coldroom was activated, the control system was programmed to ensure that the three treatments of ambient (20°C) in vessels one and three, 5°C in vessels two and four, and -5°C in vessels five and six were imposed on the ventilating air for the composters.

Although temperature data and calculated heat evolution values were continuously displayed and updated every 15 seconds on the computer monitor during a run, data were only stored to temperature and energy data files at hourly intervals throughout the duration of the experiment. The stored data were the mean values of all measurements during the hour interval. Gas concentrations for each vessel were continuously displayed on the monitor, but were only updated immediately before the solenoid valve for the given vessel was switched off. This occured approximately every eight minutes and provided sufficient time for the output from each of the analyzers to stabilize between readings. Gas concentrations for all vessels were stored to file after all six vessels had been sampled. Airflow was measured and recorded every ten to fifteen hours.

Once microbial activity declined, (producing temperatures less than 25 °C), the aeration lines were disconnected, composter vessels extracted from the water bath, and material removed from reactors. The material was weighed and recorded and sampled again for moisture content, total nitrogen, total soluable carbon, total carbon, organic matter content, and ash content. New material was again mixed and the experiment repeated.

Moisture content, organic matter content, and ash content were determined according to the Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils (ASTM, 1987).

Gas analyzers were spanned and zeroed with the proper gases before every experimental run.

5.3.1. Bomb calorimetry

Bomb calorimetry was done in triplicate on initial and final compost samples of R7 and R8 using an automatic calorimeter (AC-300,Leco Corporation, St. Joseph, MI). Run R6 was not sampled as both R6 and R7 were identical experimental designs and values measured from the bomb calorimetry from R7 would justify the correct range in heat production for the preliminary runs. The total energy content values obtained from burning the samples were used to provide an indication of the range of heat production to be expected, and were not used to test the hypothesis stated in section 1.2.2..

5.3.2. Data analysis

All statistical analysis was done using the statistical program SAS, (1994). Reported mean comparisons were analyzed using general linear model procedures SAS PROC-GLM, two tailed T tests (LSD), Duncan's multiple range test, and the Least Squares Means (see Appendix).

Due to the differences in experimental designs, any statistical analysis on any values measured during or after studies, except ventilation parameters, were conducted seperately. Values recorded in R6 and R7 were treated together as a completely randomized design while R8 was treated as a one-way or two-way completely randomized design unless otherwise mentioned.

All data used in analysis and presented for each vessel are taken from the time the compost temperature exceeded the recorded ambient temperature, peaked at the thermophilic range, and decreased to 35°C.

5.4. Results

Experiment R6 lasted the shortest amount of time overall (approximately 100 h), while experiments R7 and R8 both lasted approximately 160 h. However, the period of thermophilic temperatures (≥ 40°C) for all vessels in R6 averaged 75 h, in R7 90 h (except vessel one), and in R8 110 h. In R8, treatments of +5 and -5°C were applied at 30 h. Previous to this time all vessels were receiving air at ambient temperature (20°C).

During R6, vessel two did not remain sealed from the surrounding water bath and accumulated a significant amount of moisture. This caused some of the data to be invalid (i.e. compost temperature, change in compost mass and moisture content, and any thermal analysis). The seal on vessel one also failed during R7. However, the amount of water that leaked into the composting chamber had little affect on the systems operations and no data were lost. To avoid skewing of the data, values related in any way to a heat analysis from both of these two vessels were not used in any statistical analysis.

5.4.1. Temperature

Graphs of compost temperatures for R6, R7 and R8 are shown in Figures 5.4, 5.5, and 5.6, respectively. Water bath temperatures are not shown as these data followed very closely to temperatures collected from the compost. The composters for runs R6 and R7 were aerated with air just below ambient temperatures. The mean aeration temperature of all vessels was 15.2°C for R6 and 17.7°C for R7[3]. Mean ventilating air temperatures for the ambient, +5, and -5°C treatments in run R8 were 14.8, 4.7, and -5.2°C respectively.

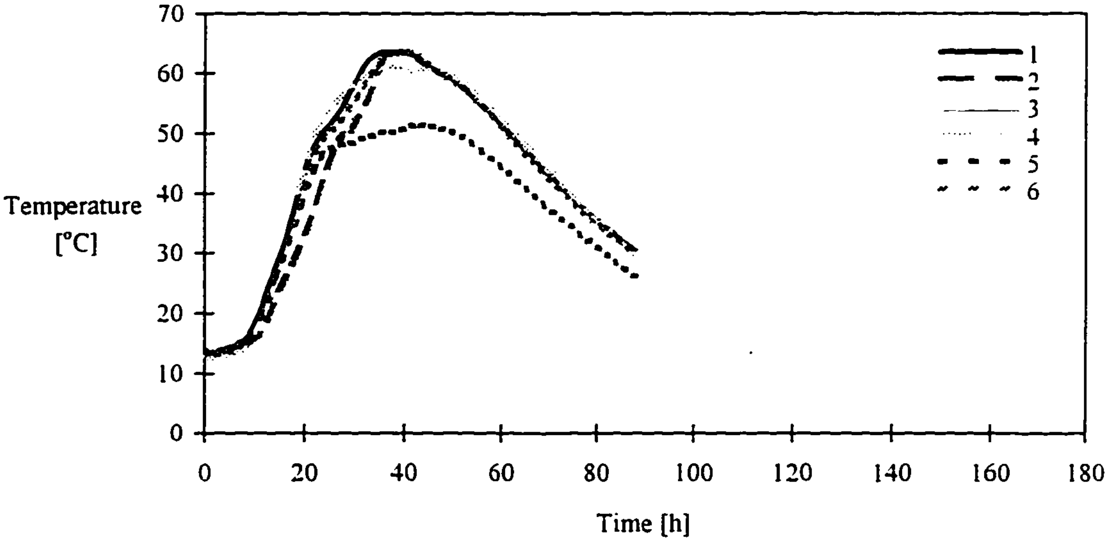

FIGURE 5.4 COMPOST TEMPERATURE FOR CONTROL RUN R6

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[3] The mean aeration temperature of all the vessels for R7 does not include vessel one as this vessel malfunctioned. The average temperature of the ventilating air for vessel one was 26.8°C.

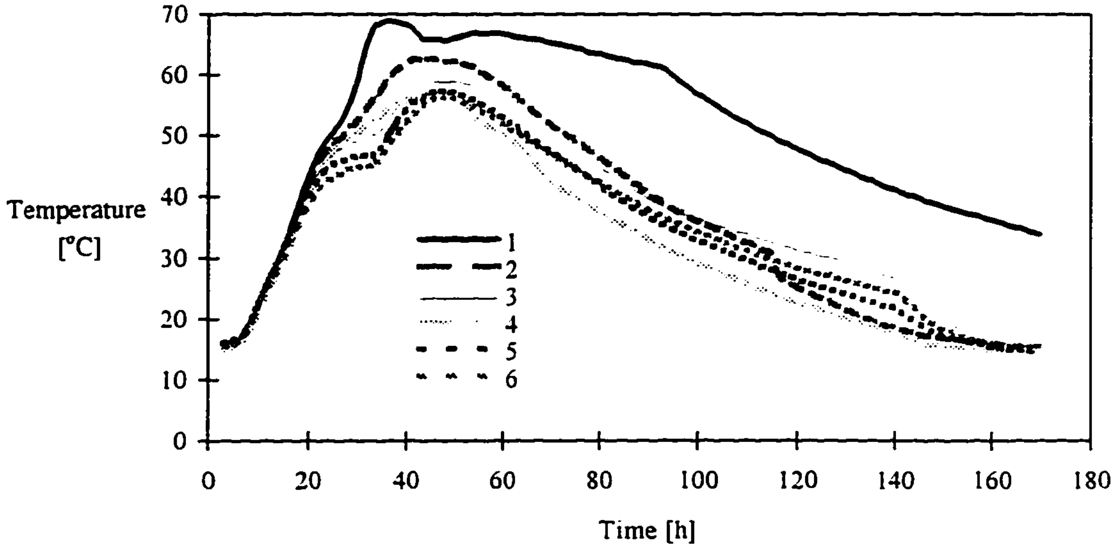

FIGURE 5.5 COMPOST TEMPERATURE FOR CONTROL RUN R7

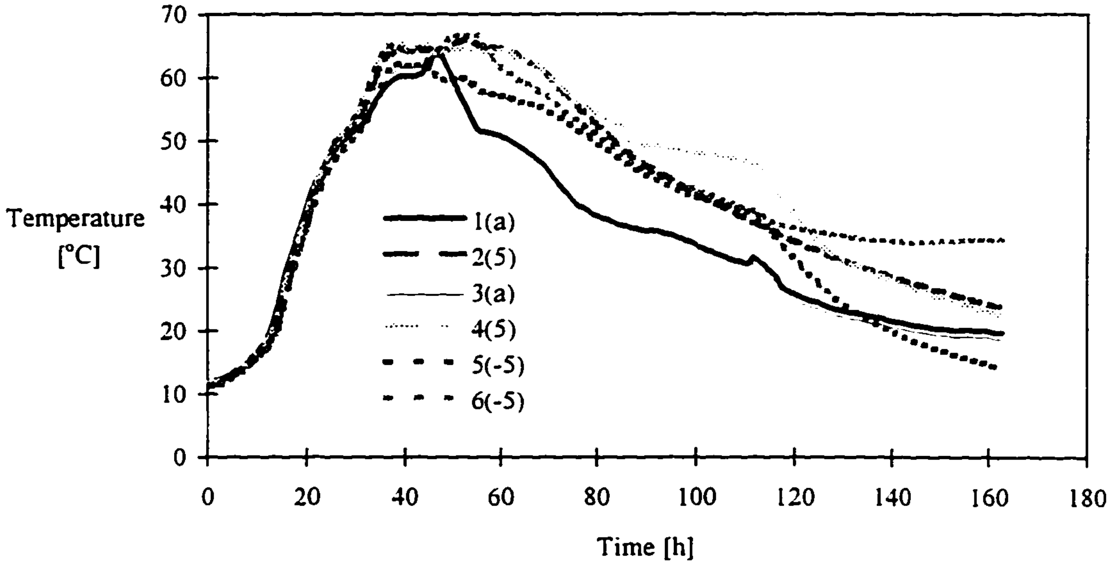

FIGURE 5.6 COMPOST TEMPERATURE FOR RUN R8

5.4.2. Gas concentrations

Gas concentration data are shown for each vessel for all three runs in Figures 5.7 to 5.15. Oxygen consumption curves are displayed in Figures 5.7, 5.9 and 5.11, while CO_2 production is presented in Figures 5.8, 5.10 and 5.12. Ammonia production for R6, R7, and R8 is shown in Figures 5.13, 5.14, and 5.15 respectively. The gas concentration data were converted to mass and are shown in the plots as cumulative values rather than instantaneous values. Rates of NH_3 and CO_2 production and O_2 consumption can be inferred from the slopes of the plots. Run R7 produced very little ammonia in comparison to R6 and R8. This is shown in Figure 5.14 and can also be seen in Table 5.1 which contains the total amount of O_2 consumed, and CO_2 and NH_3 produced. Table 5.2 shows the mean air flow rates and total air received in each run. Numbers in parentheses in Table 5.1 and 5.2 are the standard deviations. In Table 5.1 $n=6$ for R6 and R7 and $n=2$ for each treatment of R8. The number of observations used to calculate the standard deviation in Table 5.2 varied between vessels according to the number of airflow measurements that were recorded during each experiment.

TABLE 5.1 MEAN VALUES OF CUMULATIVE O_2 CONSUMPTION, CO_2 AND NH_3 PRODUCTION

Experimental run	Mean O_2 Consumption [g vessel^{-1}]		Mean CO_2 Production [g vessel^{-1}]		Mean NH_3 Production [g vessel^{-1}]	
R6	183	(56.2)	83	(53.0)	0.35	(0.08)
R7	73	(9.2)	46	(40.9)	0.15	(0.03)
R8(a)	70	(2.0)	30	(5.2)	0.89	(0.02)
R8(+5)	114	(2.2)	73	(9.3)	0.85	(0.23)
R8(-5)	102	(24.0)	57	(31.2)	0.86	(0.06)

TABLE 5.2 MEAN VALUES OF AIR FLOW AND AIR RECEIVED

Experiment & vessel	Mean Rate of Air Flow [L·min^{-1}]		Mean Rate of Air Flow [L·kg(DM)$^{-1}$·h^{-1}]	Total Air Received [m^3·vessel^{-1}] [a]
R6-1	2.02	(0.09)	225	8.72
R6-2	1.86	(0.11)	208	2.81
R6-3	1.89	(0.13)	227	8.39
R6-4	1.85	(0.10)	183	8.11
R6-5	1.83	(0.08)	216	7.27
R6-6	1.68	(0.11)	196	7.20
R7-1	0.42	(0.06)	44	3.94
R7-2	0.88	(0.00)	102	5.04
R7-3	0.95	(0.06)	110	5.78
R7-4	1.06	(0.08)	117	5.25
R7-5	1.20	(0.06)	143	6.50
R7-6	1.07	(0.06)	125	5.50
R8(a)-1	0.88	(0.16)	115	4.55
R8(a)-3	0.77	(0.11)	98	3.82
R8(+5)-2	0.65	(0.10)	81	4.20
R8(+5)-4	0.75	(0.16)	96	4.69
R8(-5)-5	0.76	(0.13)	100	4.30
R8(-5)-6	0.66	(0.15)	88	4.63

[a] Calculated according to the length of time for the compost temperature to peak and return to 35 °C.

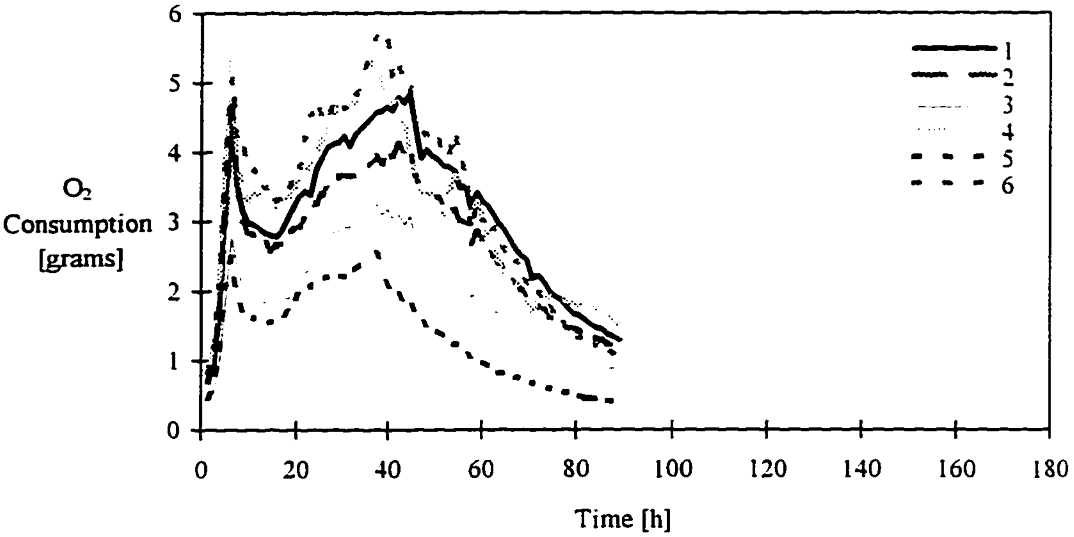

FIGURE 5.7 CONSUMPTION OF OXYGEN DURING RUN R6

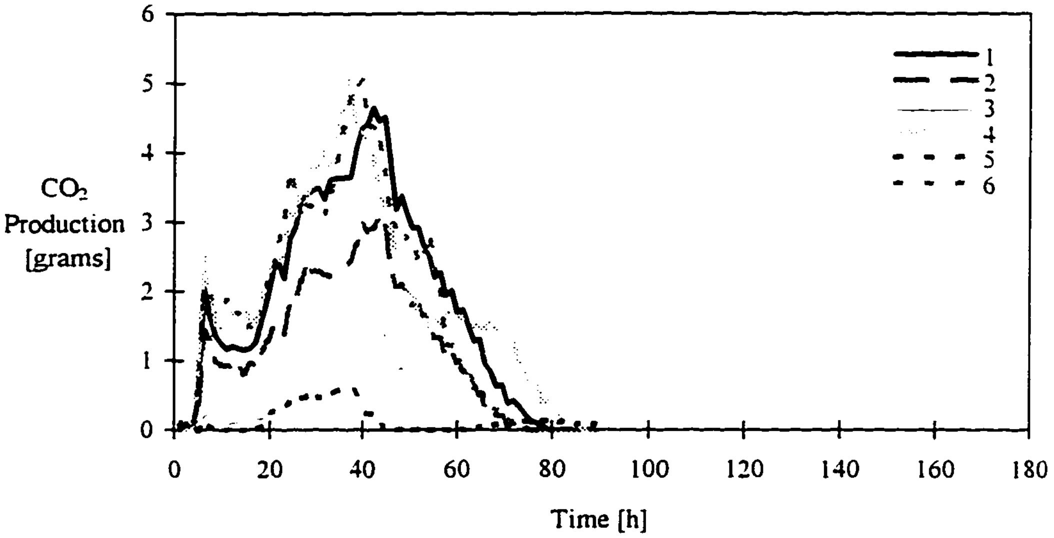

FIGURE 5.8 CARBON DIOXIDE PRODUCTION DURING RUN R6

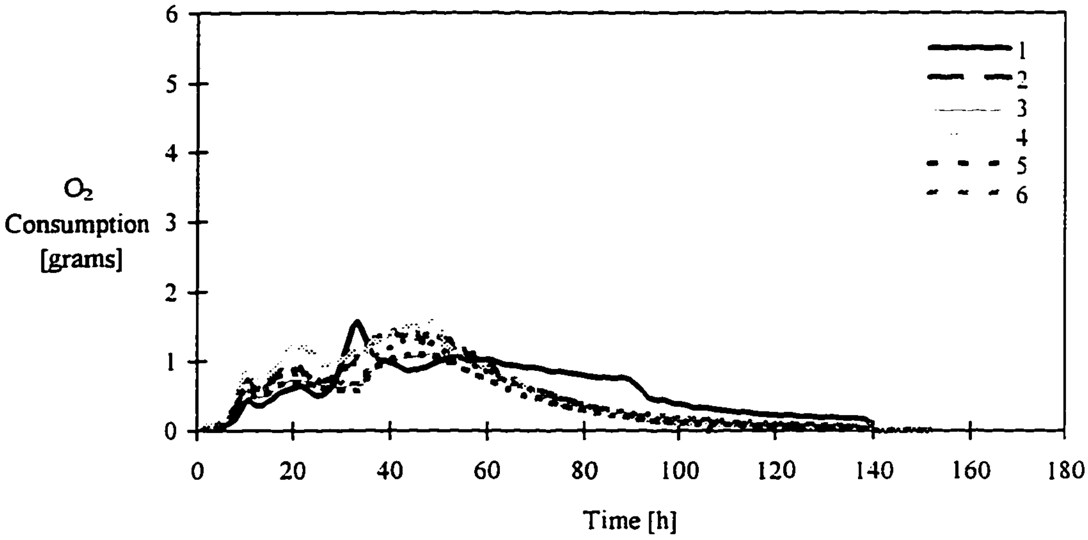

FIGURE 5.9 OXYGEN CONSUMPTION DURING RUN R7

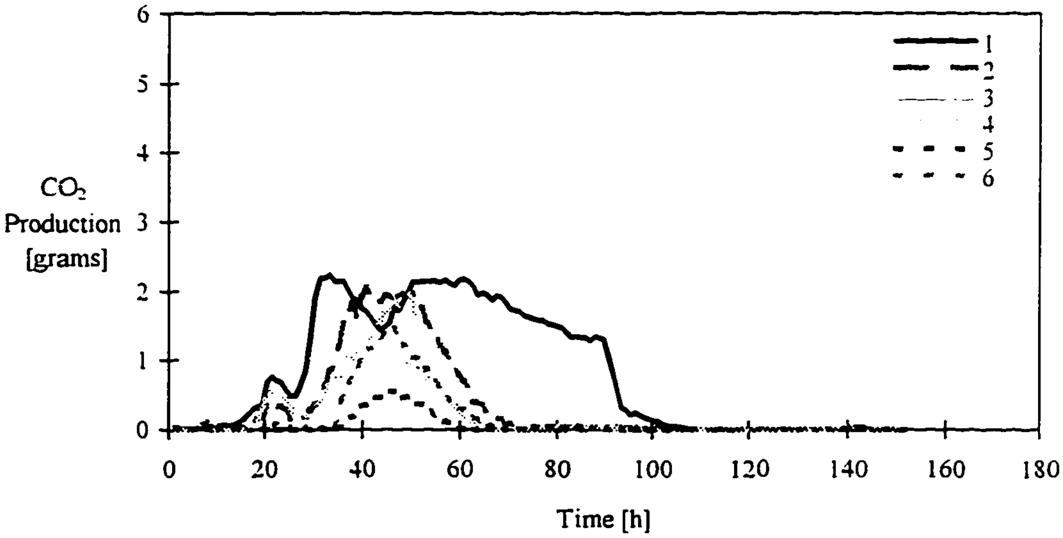

FIGURE 5.10 CARBON DIOXIDE PRODUCTION DURING RUN R7

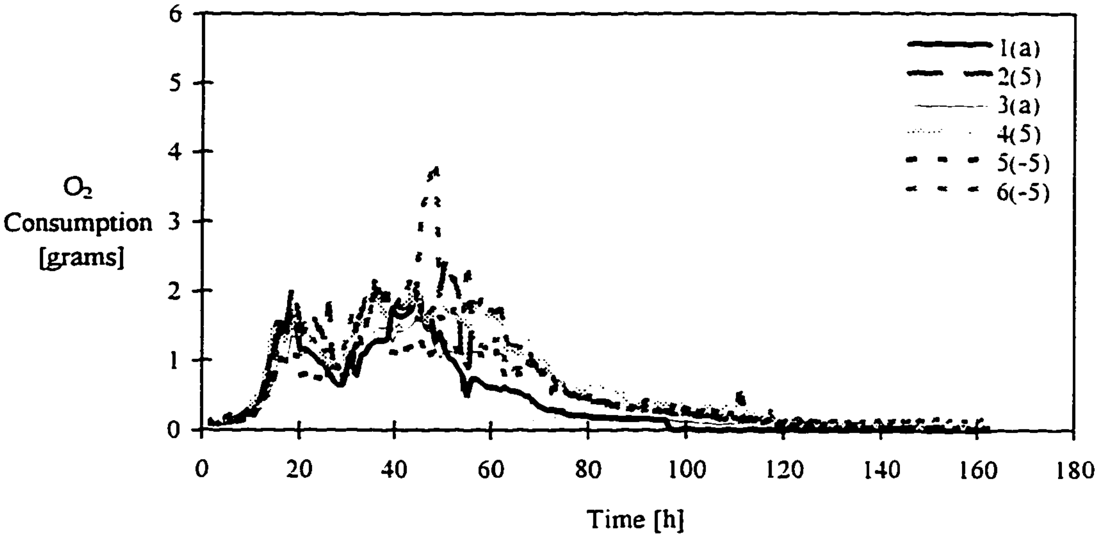

FIGURE 5.11 OXYGEN CONSUMPTION DURING RUN R8

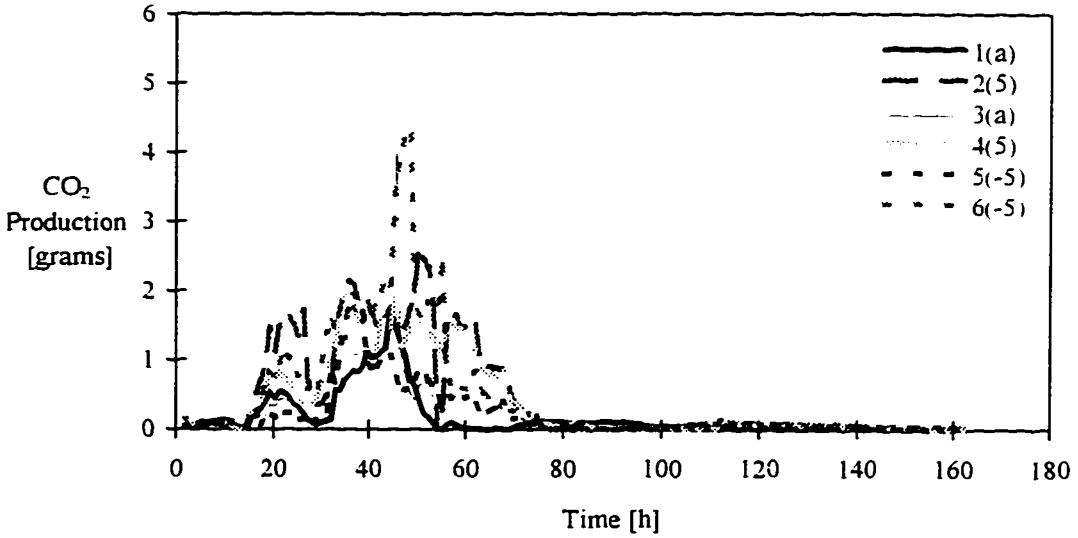

FIGURE 5.12 CARBON DIOXIDE PRODUCTION DURING RUN R8

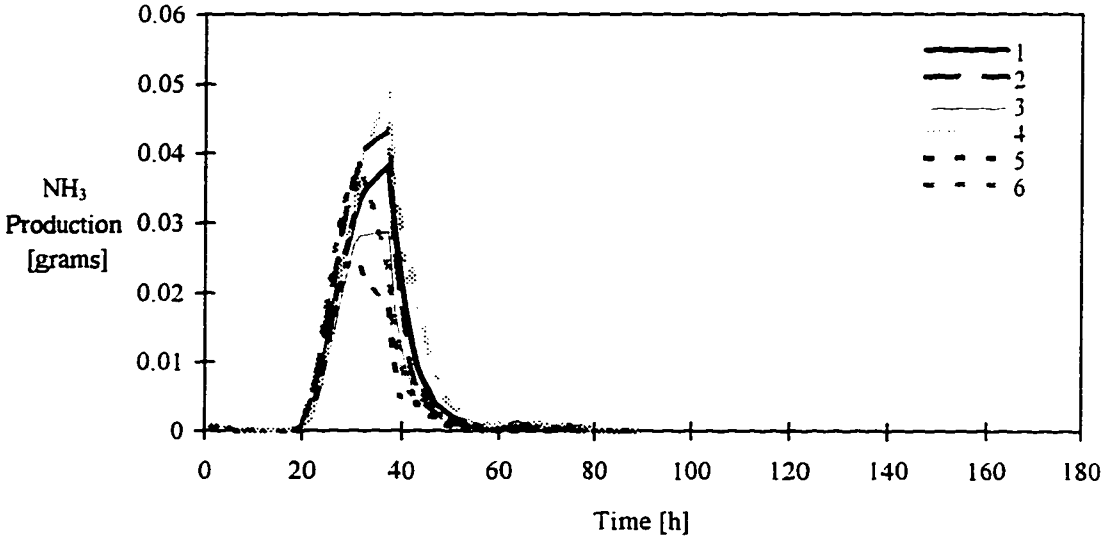

FIGURE 5.13 AMMONIA PRODUCTION DURING RUN R6

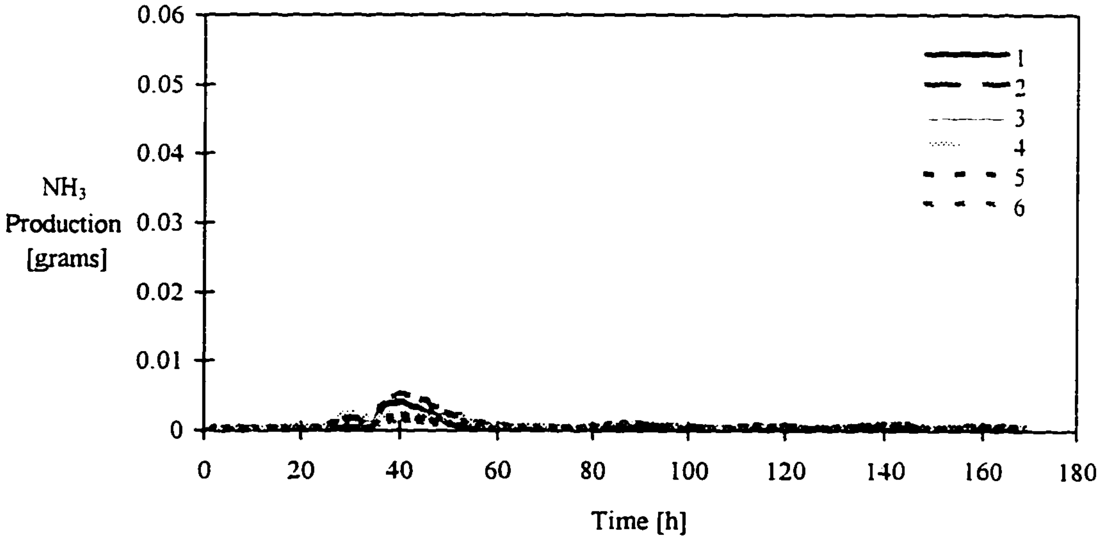

FIGURE 5.14 AMMONIA PRODUCTION DURING RUN R7

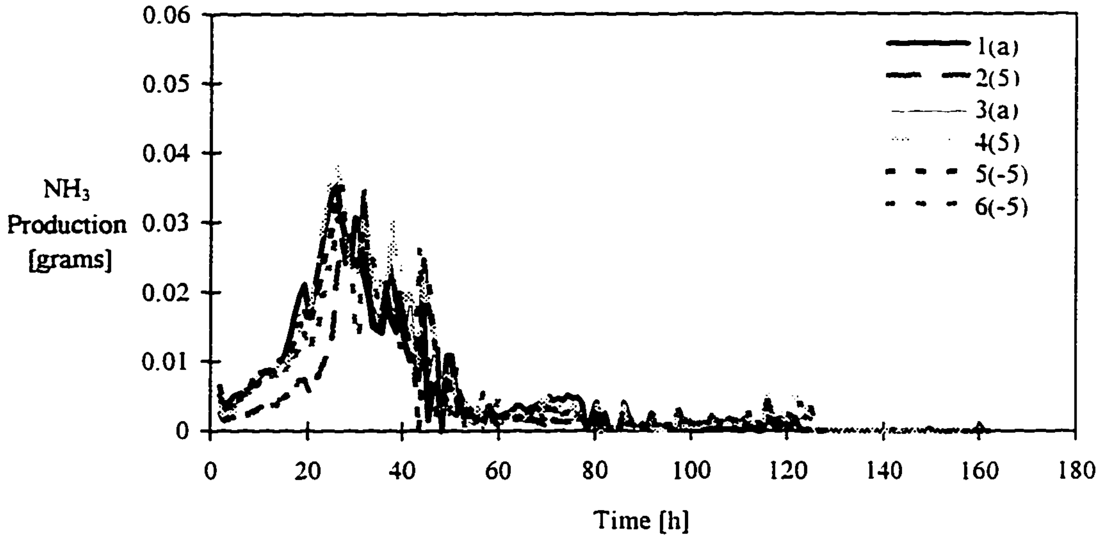

FIGURE 5.15 AMMONIA PRODUCTION DURING RUN R8

Large discrepancies existed in the amounts of O_2 consumed and CO_2 produced between vessels in runs R6 and R7 as shown by the high values in standard deviations. Yet at $p=0.05$, differences in CO_2 production were not significant while consumption of O_2 were found to be significantly different. Ammonia production was also significantly different between R6 and R7. In R8 the -5 treatment also exhibited large differences between replicates in respiratory gas exchange, however, no significant difference was found between treatments ($p>0.05$).

The large values in standard deviations may be attributed to small degrees of error in each individual reading in both the oxygen and carbon dioxide analyzers. The Beckman 864 infrared carbon dioxide analyzer available for use in all three trials was old and after long usage did display difficulties in accurately measuring CO_2 concentrations to ± 200 ppm at concentrations <700 ppm. At concentrations >700 ppm, accuracy improved to ± 20 ppm. The accuracy available in the Servomex O_2 and Beckman 870 NH_3 gas analyzers was estimated at ± 5 and ± 0.5 ppm respectively. No hysteresis was detected in any of the gas analyzers. Due to the potentially large error in O_2 and CO_2 readings, any calculated values of respiratory quotients will appear inconsistent to those reported for typical microbial respiration. Although the quantitative data recorded for O_2 consumption and CO_2 evolution should be regarded with caution and not be used in analysis, the data represents very well the qualitative characteristics seen for aerobic decomposition. The production of CO_2 is reflected graphically (Figures 5.14 to 5.18) by the consumption of O_2 during each composting trial. As well, a typical 'two peak' curve due to mesophilic and thermophilic decomposition (Jackson and Line, 1997; Carlyle and Norman, 1941) can be distinguished from the oxygen and carbon dioxide graphs in all three runs.

In all three runs the only statistically significant differences ($p < 0.05$) between variables that might have had an influence on the rate of decomposition were the total amounts of air received and the ventilating flow rate (Table 5.2). Total mean volume of air received per vessel in R6 was significantly greater than the means received in R7 and R8. Again, mean ventilating air flow rates per initial dry mass in R6 were significantly greater than the mean flow rates in R7 and R8. However, no differences were found amongst the mean volumes of air received per vessel or the rate of air flow per initial mass between treatments in R8, or between R7 and R8.

5.4.3. Compost properties

Table 5.3 lists all the initial and final masses, moisture contents, C:N ratios, ash contents, and length of activity[4] of each individual composter for the three runs. Also shown are the amounts of water lost through vaporization in the ventilating air during each run.

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[4] Length of run was calculated as the time required for the compost temperature to peak and return to 35°C.

Moisture contents, C:N ratios and ash contents were analysed in triplicate from representative samples taken from each vessel. As vessel two in R6 and vessel one in R7 malfunctioned, the data that are presented for these composters should be regarded with caution.

It was extremely difficult to collect a representative sample of the remaining substrate because of the large moisture gradient in the material. Substrate at the bottom of the vessel was always extremely dry, while substrate near the top of the composter was always found to be extremely wet. This made it very difficult to accurately measure the moisture content of the remaining substrate and created some degree of error in all values relating to final dry mass and final volatile dry mass. Thus, more emphasis should be put on comparing total heat outputs and total heat outputs per unit initial dry mass as opposed to values measured in relation to final dry mass.

Little error is expected in moisture contents of initial manure straw mixtures. Initial mixtures were well mixed and excellent representative samples were obtained.

The possibility of error in the final moisture readings is apparent in an overall moisture balance. Table 5.3 shows total mass of water removed by the ventilating air through vaporization. This was calculated by subtracting the total mass of water entering the composter through ventilation from the total mass of water exiting. However, the amount of water lost from the composting substrate (i.e. initial water content subtract the final water content) for some of the vessels in each run does not correspond correctly with the amount removed. Although possible errors in the values for final moisture content may provide some explanation, other factors may have also contributed to these discrepencies. Such factors may have included the relative humidity of the inlet air which was determined through the wet and dry bulb temperatures measured with a sling psychrometer.

Statistical analysis comparing the mean initial wet mass of compost in each vessel showed no differences ($p > 0.05$) between all three runs. Yet, the mean initial dry masses for

R8 were found to be significantly less than those for R6 and R7. However, this difference will have no effect on discrepancies in heat production between experiments as values for heat output are reported as kilojoules per initial dry mass. As well, because of the different experimental design of R8 and that of R6 and R7, values of heat output between all three experiments are not directly comparable. The initial C:N ratios and moisture and ash content were not compared between trials. However, Table 5.3 shows the values for these parameters to be very similar and, therefore, should have had no effect on the amount of heat produced from each composter.

Despite possible errors, the percentage of mass lost for all three runs was typical for bench-scale studies, ranging from 12 to 25%. Hogan *et al.*, (1989) in a similar study composting rice hulls, reported percentages of mass loss of 16.9 and 15.7%.

No differences were detected between the amounts of dry matter (DM) and volatile dry matter (VDM) lost between between R7 and those values measured for R6 ($p > 0.05$). As well, no significant differences ($p > 0.05$) were found amongst treatments in R8 in the amount of DM and VDM lost. Interestingly, the amount of water lost through vaporization is reflected by the amount of VDM lost. Vessel number four in R8 (treatment +5) yielded the highest decrease in volatile solids, while vessel number three (treatment ambient) exhibited the least amount of volatile solids lost. Vessel four also released the most amount of water and vessel three lost the least amount of water of all the vessels in R8. This does support reports that the amount of volatile solids that are lost are directly proportional to the amount of water released (MacGregor *et al.*, 1981: Papadimitiou and Balis, 1996).

Initial moisture contents in all three runs ranged from 78 to 80 %. Most researchers report a lower range of 60 to 70% for optimal composting (Keener *et al.*, 1996: Robinson and Stentiford, 1993; Poincelot, 1972; Shulze, 1965). Determining the best moisture content to maximize the rate of degradation, however, is a function of the organic material being composted and the rate of ventilation. Jeris and Regan (1973) cite a report by Gotaas (1956) who found the optimum range of moisture content to be 75 to 80% for composting manure and straw. The rate of ventilation used in the study was not given. Thermophilic conditions were quickly achieved in all runs, thereby proving that the excessive moisture was not inhibiting metabolism, and manure/straw mixtures can be composted at high moisture contents. The high rate of ventilation used also undoubtedly helped in providing sufficient gas exchange and heat removal.

The amount of time it took for the compost in each unit to reach thermophilic conditions, maintain thermophilic conditions, and decrease in temperature to 35°C is also reported in Table 5.3. Significant differences did exist between times for R6 and R7, as well as between the ambient treatment and the +5 and -5 treatment ($p<0.05$) in R8. However, both treatments with altered temperatures (+5 and -5) lasted longer than the ambient treatment, as well as the vessels in R6 and R7. These differences in time support the idea that the lowered ventilation temperature did affect on the rate of microbial activity within the compost.

TABLE 5.3 CHARACTERISTICS OF COMPOSTING MATERIAL FOR RUNS R6, R7, AND R8

Initial

Expermental run	Run Length Until 35°C [h]	Total Wet Mass [g]	MC [%]	Volatile Matter [%]	C:N Ratio	Total dry Mass [g]	Total Ash Mass [g]	Total Volatile Dry Mass [g]
R6-1	81	2425	77.8	14	44	538	75	463
R6-2	-	2408	77.8	14	44	535	75	460
R6-3	86	2244	77.8	14	44	498	70	428
R6-4	81	2726	77.8	14	44	605	85	520
R6-5	74	2298	77.8	14	44	510	71	439
R6-6	80	2318	77.8	14	44	515	72	443
R7-1	165	2563	78.1	13	44	561	73	488
R7-2	103	2372	78.1	13	44	519	68	452
R7-3	105	2376	78.1	13	44	520	68	453
R7-4	86	2488	78.1	13	44	545	71	474
R7-5	94	2310	78.1	13	44	506	66	440
R7-6	98	2348	78.1	13	44	514	67	447
R8(a)-1	96	2279	80.0	14	44	456	64	392
R8(a)-3	99	2348	80.0	14	44	470	66	404
R8(+5)-2	118	2379	80.0	14	44	476	67	409
R8(+5)-4	123	2362	80.0	14	44	472	66	406
R8(-5)-5	116	2268	80.0	14	44	454	64	390
R8(-5)-6	130	2258	80.0	14	44	452	63	388

Table 5.3 (continued) Characteristics of composting material for runs R6, R7, and R8

Final

Expermental run	Total Wet Mass [g]	MC [%]	Volatile Matter [%]	C:N Ratio	Total dry Mass [g]	Total Ash Mass [g]	Total Volatile Dry Mass [g]
R6-1	1548	73.2	16	44	415	66	348
R6-2	-	80.0	14	44	-	-	-
R6-3	1480	76.8	16	44	343	55	288
R6-4	1679	76.7	15	44	391	59	333
R6-5	1484	73.3	15	43	396	59	337
R6-6	1580	73.6	16	43	417	67	350
R7-1	2327	82.6	15	43	405	61	344
R7-2	1439	75.5	15	43	353	53	300
R7-3	1374	67.0	14	43	453	63	390
R7-4	1662	71.1	15	43	480	72	408
R7-5	1266	70.4	15	43	375	56	319
R7-6	1446	68.9	14	44	450	63	387
R8(a)-1	1300	70.6	17	42	382	65	317
R8(a)-3	1490	72.3	17	42	413	70	343
R8(+5)-2	1601	73.7	18	42	421	76	345
R8(+5)-4	1650	78.5	18	43	355	64	291
R8(-5)-5	1519	75.7	17	43	369	63	306
R8(-5)-6	1436	75.0	19	43	359	68	291

TABLE 5.3 (CONTINUED) CHARACTERISTICS OF COMPOSTING MATERIAL FOR RUNS R6, R7, AND R8

Total Mass Loss

Expermental run	Total Wet Mass [g]	Total dry Mass [g]	Total Volatile Dry Mass [g]	Dry Mass Loss [%]	Volatile Mass Loss [%]	Total Water Lost in Ventilation [g]
R6-1	877	123	114	22.9	24.7	1053
R6-2	-	-	-	-	-	-
R6-3	764	155	140	31.1	32.7	1024
R6-4	1047	214	188	35.4	36.1	985
R6-5	814	114	102	22.3	23.2	609
R6-6	738	97	92	18.9	20.8	859
R7-1	236	156	144	27.9	29.5	580
R7-2	933	167	152	32.1	33.7	623
R7-3	1002	67	63	12.9	13.9	619
R7-4	826	65	66	11.8	13.9	556
R7-5	1044	131	122	25.9	27.6	669
R7-6	902	65	61	12.5	13.5	546
R8(a)-1	979	74	75	16.2	19.2	588
R8(a)-3	858	57	61	12.1	15.2	558
R8(+5)-2	778	55	64	11.5	15.6	719
R8(+5)-4	712	118	115	24.9	28.4	806
R8(-5)-5	749	84	84	18.6	21.5	588
R8(-5)-6	822	93	98	20.5	25.1	703

5.4.4. Heat evolution

The cumulative evolution of heat, and the rate of heat generation for all vessels were also graphed against time and are shown in Figure 5.16 to 5.21 respectively. Table 5.4 summarizes the results of all thermal analysis done for each run. Although the analysis used to determine heat outputs did not utililize equation 3.2 but rather calculated heats on the basis of enthalpies, this will not have greatly affected values obtained for heat output and rate of heat production. Total heat output was determined by the heat lost or gained through conductive losses added to the difference in enthalpy of the outlet and inlet air. Heat output per unit dry mass lost and the rate of heat output per initial unit volatile dry mass shown in Table 5.4 were calculated using the corrected heat values (i.e. conductive losses added to heats calculated from enthalpy changes in ventilation).

The total ventilative heat output, heat lost/gained through conduction and the percent conductive heat lost/gained were all significantly different between R6 and R7 ($p < 0.05$). A comparison of means of the same variables between treatments in R8 showed significant differences only in the amounts of heat measured from ventilation air between the +5°C and the ambient treatment. Surprisingly, despite the high values in the percentage of conductive heat lost or gained, no significant differences were found between treatments.

Other values tested for significant differences between R6 and R7 and between treatments in R8 included mean total heat output, heat output per unit dry mass lost, rate of heat output per initial unit volatile dry mass, and peak and average rates of heat output of each run. No significant differences ($p > 0.05$) were found between the above mentioned variables, from Table 5.4, for all three treatments in R8. The mean total heat produced, and the peak and average rate of heat evolved, were statistically analyzed and values were found to be significantly different between R6 and R7 ($p < 0.05$). However, heat evolution per unit dry mass lost, and the maximum heat output per initial unit volatile dry mass showed no significant differences between R6 and R7 ($p > 0.05$). The p value ($p = 0.0577$) for the maximum amount of heat evolved per dry matter initially composted was close to the level of significance. In Table 5.4, the mean maximum heat output for R6 was decreased by the value measured for vessel five. This in turn increased the p value, resulting in a nonsignificant test. A nonsignificant difference between R6 and R7 is arguable, as Table 5.4 shows that the majority of values are much greater in R6 than R7. Eliminating vessel five from the test results in the mean maximum heat output between R6 and R7 being significantly different ($p = 0.0037$).

For R8, a comparison of means was performed on the rate of thermal energy produced in the two replicates of each treatment at ten hour intervals from 20 to 90 h (Figure 5.22). This aided in understanding the effects of different ventilation temperatures on the composting process. The rate of thermal energy production did not vary significantly at the five percent level between treatments until 30h had elapsed. Significantly different rates of heat evolution were produced in the -5 treatment after 30h and up to 60h (Table 5.5). At 60 h both the +5 and the -5 treatments exhibited a significantly higher rate of heat evolution than the ambient treatment. After 60h all three treatments had similar rates of heat evolution.

Results from bomb calorimetry done in triplicate on samples from runs R7 and R8 are tabulated in Table 5.6. The values in brackets are the standard deviations ($n=3$). Total heat produced in respect to the amount of dry matter lost through combustion was analyzed and is shown in Table 5.6 as total energy content. Bomb calorimetric values in R7 did not vary significantly from measured values (Table 5.4). A nested-split plot design was applied to R8 to test for significant differences. No variances were calculated between the two methods of determination (bomb calorimetry and ventilatively) amongst treatments, nor between mean values of heat evolution for each method of measurement in R8.

TABLE 5.4 HEAT ANALYSIS

Expermental run	Peak Heat Output [W]	Average Heat Output [W]	Total Heat Output [kJ]	Total Ventilative Heat Output [kJ]	Heat Lost/Gained via Conduction [kJ][a]	Conductive Heat Output [%]
R6-1	20	10	2631	2974	343	13
R6-2	-	-	-	-	-	-
R6-3	25	11	3054	2957	-97	3
R6-4	24	11	2869	2819	-49	2
R6-5	12	7	1627	1679	52	3
R6-6	28	10	2466	2452	-13	1
R7-1	12	3	1371	1598	227	17
R7-2	16	4	1384	1770	386	28
R7-3	15	4	1357	1742	385	28
R7-4	15	4	1176	1505	329	28
R7-5	16	5	1470	1834	364	25
R7-6	14	3	1072	1448	376	35
R8(a)-1	13	3	1020	1455	435	43
R8(a)-3	24	6	1722	1413	-309	18
R8(+5)-2	16	4	1338	1991	653	49
R8(+5)-4	32	5	2061	2235	174	8
R8(-5)-5	37	5	1843	1680	-164	9
R8(-5)-6	43	6	2654	2026	-628	24

[a] A positive value correlates to heat flowing from the water bath to the composter, while a negative value correlates to heat flowing from the composter to the water bath.

TABLE 5.4 (CONTINUED) HEAT ANALYSIS

	Dry Matter		Volatile Dry Matter	
Expermental run	Heat Output per DM lost $[kJ\cdot(gDM)^{-1}]$	Maximum Heat Output $[J\cdot(gDM)^{-1}\cdot h^{-1}]^{a}$	Heat output per VDM lost $[kJ\cdot(gVDM)^{-1}]$	Maximum Heat Output $[J\cdot(gVDM)^{-1}\cdot h^{-1}]^{b}$
R6-1	21	133	23	155
R6-2	-	-	-	-
R6-3	20	179	22	208
R6-4	13	141	15	164
R6-5	14	85	16	98
R6-6	25	198	27	230
R7-1	9	75	10	87
R7-2	8	109	9	125
R7-3	20	104	22	119
R7-4	18	99	18	113
R7-5	11	114	12	131
R7-6	17	96	18	110
R8(a)-1	14	101	14	117
R8(a)-3	30	182	28	212
R8(+5)-2	24	119	21	139
R8(+5)-4	18	243	18	283
R8(-5)-5	22	290	22	337
R8(-5)-6	29	336	27	391

[a] The grams DM is initial loading. Maximum heat output was measured for one hour.

[b] The grams VDM is initial loading. Maximum heat output was measured for one hour.

TABLE 5.5 COMPARISONS OF MEAN HEAT PRODUCTION (W) BETWEEN TREATMENTS FOR R8[a]

Treatment	Time							
	20	30	40	50	60	70	80	90
Amb	2.08^a	3.95^a	10.52^a	8.77^a	4.18^a	3.52^a	2.28^a	1.40^a
+5	2.27^a	3.98^a	11.07^a	8.79^a	8.28^b	3.87^a	3.13^a	1.50^a
-5	2.37^a	2.58^a	18.83^b	13.78^b	7.95^b	4.75^a	3.20^a	1.68^a

[a] Means with the same letter at any time were not significantly different ($p > 0.05$).

TABLE 5.6 TOTAL ENERGY CONTENT AS PER BOMB CALORIMETRY

Expermental run	Initial Heat of Combustion $[\mathrm{kJ}\cdot(\mathrm{gDM})^{-1}]$		Final Heat of Combustion $[\mathrm{kJ}\cdot(\mathrm{gDM})^{-1}]$		Total Energy Lost [kJ]
R7-1	17.63	(0.03)	17.19	(0.29)	2933
R7-2	17.63	(0.03)	16.57	(0.61)	3317
R7-3	17.63	(0.03)	16.87	(0.01)	1524
R7-4	17.63	(0.03)	16.49	(0.35)	1687
R7-5	17.63	(0.03)	17.29	(0.11)	2437
R7-6	17.63	(0.03)	17.13	(0.07)	1362
R8(a)-1	17.02	(0.09)	16.08	(0.05)	1620
R8(a)-3	17.02	(0.09)	15.91	(0.15)	1426
R8(+5)-2	17.02	(0.09)	15.93	(0.19)	1393
R8(+5)-4	17.02	(0.09)	15.59	(0.25)	2512
R8(-5)-5	17.02	(0.09)	15.83	(0.07)	1878
R8(-5)-6	17.02	(0.09)	15.61	(0.26)	2803

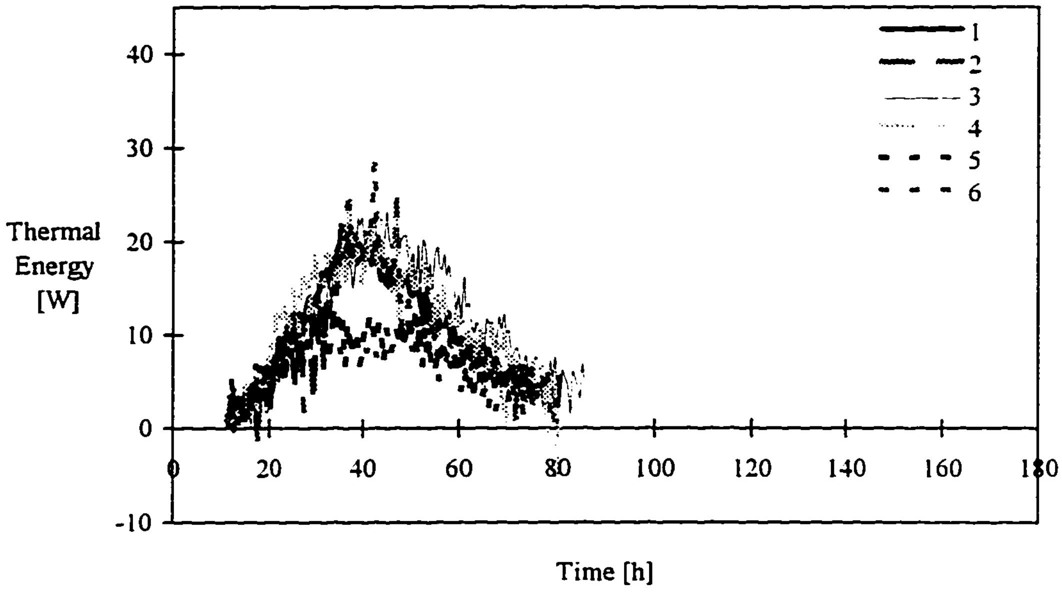

FIGURE 5.16 THERMAL ENERGY PRODUCED DURING RUN R6

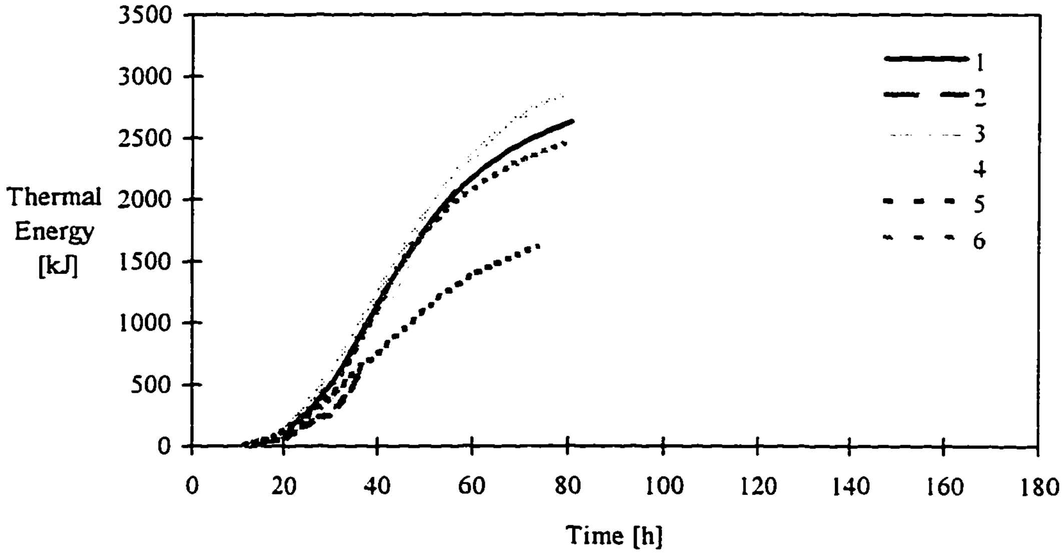

FIGURE 5.17 CUMULATIVE THERMAL ENERGY PRODUCED DURING RUN R6

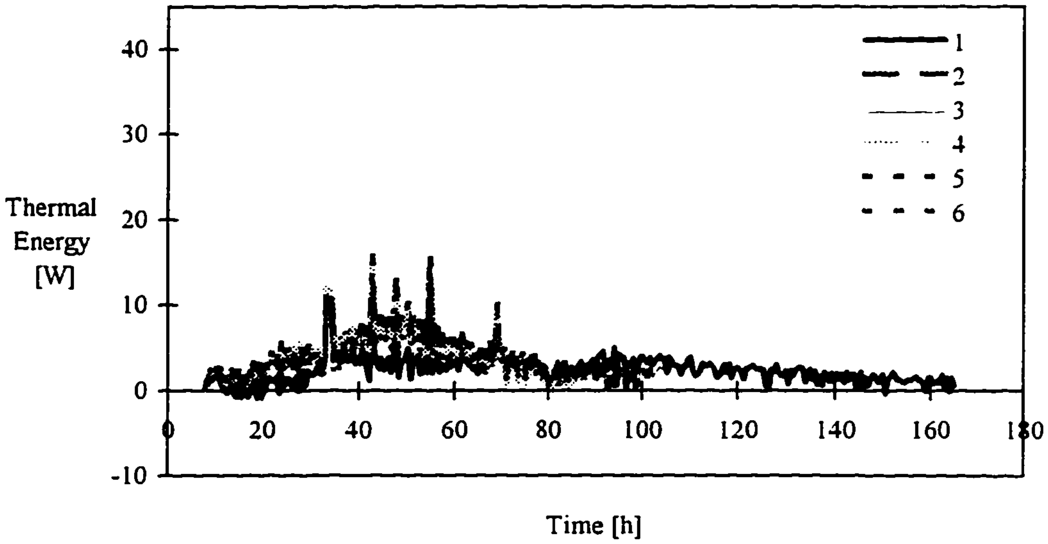

FIGURE 5.18 THERMAL ENERGY PRODUCED DURING RUN R7

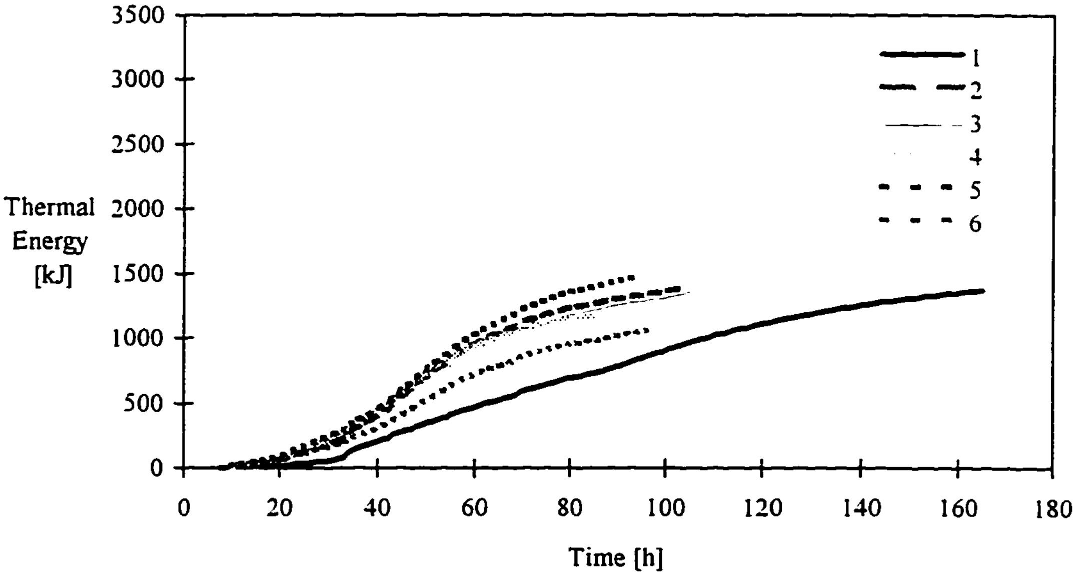

FIGURE 5.19 CUMULATIVE THERMAL ENERGY PRODUCED DURING RUN R7

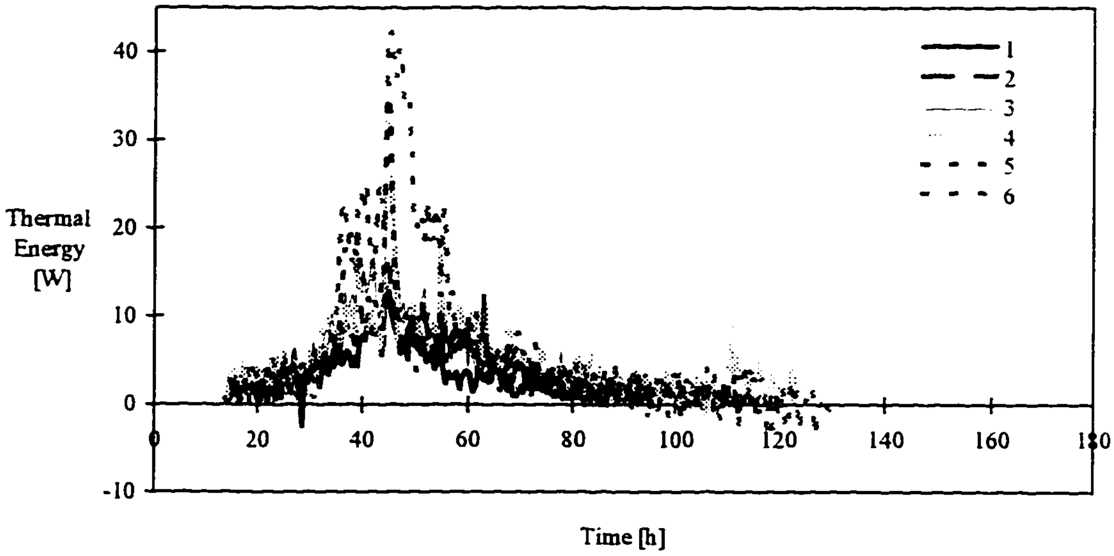

FIGURE 5.20 THERMAL ENERGY PRODUCED DURING RUN R8

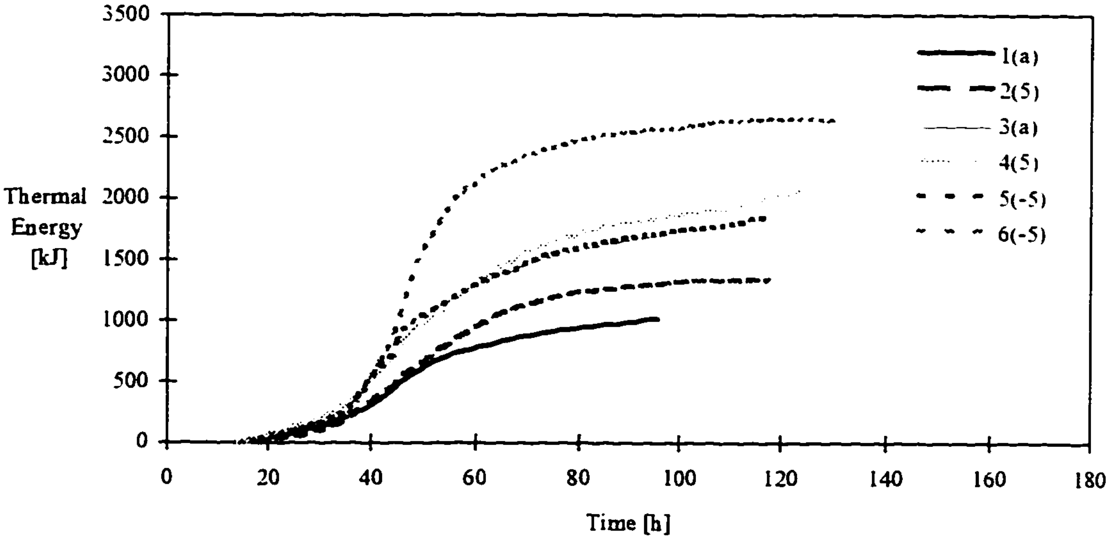

FIGURE 5.21 CUMULATIVE THERMAL ENERGY PRODUCED DURING RUN R8

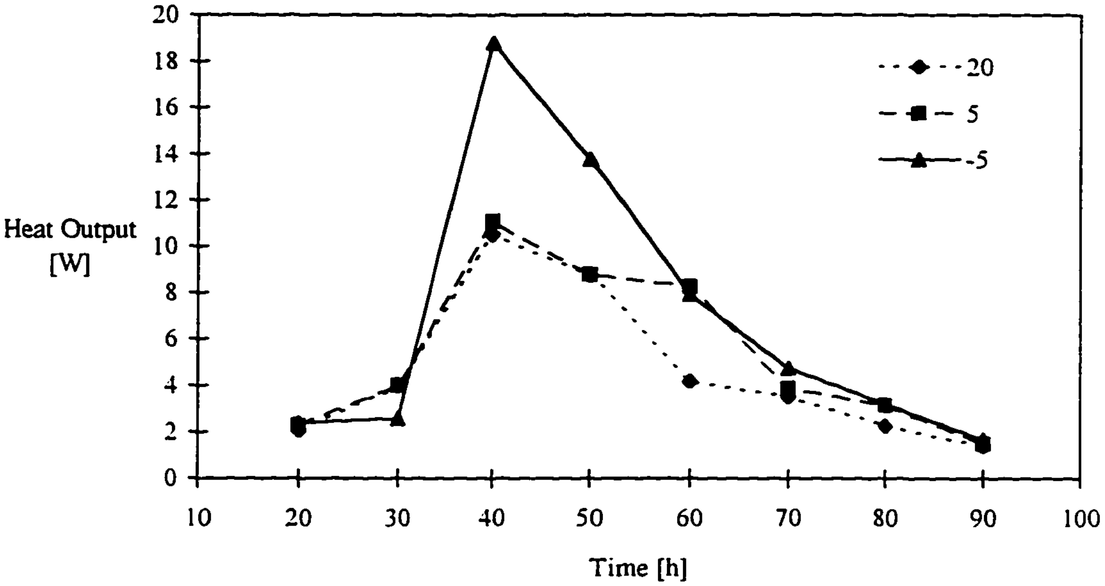

FIGURE 5.22 MEAN THERMAL ENERGY PRODUCED BETWEEN TREATMENTS DURING THERMOPHILIC CONDITIONS IN RUN R8

5.5. Discussion

5.5.1. Design

The design objective to minimize all heat flowing radially from the composting chamber was not entirely fulfilled. Several of the composters, especially in R8, gained relatively large amounts of heat from the surrounding water bath. Nonetheless, total heat outputs were compensated accordingly. Whether these larger quantities in conductive fluxes effected the rate of decompostion in the compost is doubtful. Moisture was found to be the most important operational parameter for the composting system, and is not a function of the rate of conductive heat loss.

5.5.2. Temperature

Temperature profiles in Figures 5.4, 5.5, and 5.6 show that thermophilic conditions were reached in all six vessels within 20 hours of initiation of the experiment. This indicated good reproducibility amongst experiments during the initial mesophilic stages of composting. This is also consistent with the temperature profiles displayed in the large reactors during Phase I.

The main objective of R6 and R7 was to demonstrate the repeatability of the experimental system and procedure. It was important to reproduce in each experiment the initial rise in temperature and to attain thermophilic conditions in approximate equal time frames. This was accomplished, as is shown by the temperature curves of the six vessels in Figures 5.4 and 5.5. Although the length of time of active decomposition in the vessels during R6 was shorter than that in R7 (and R8), the initial rise in temperature to thermophilic conditions in each experiment was very similar. The two sets of six curves in each figure for R6 and R7 follow the same slope for the first 20 h, or until thermophilic conditions are met. After 20h individual composters assume slightly different rates of decomposition, which is reflected by the mean temperature of the compost mass. This is possibly owing to the nonhomogeneous nature of the compost matrix. It is widely recognized that the physical and chemical nature of the substrate being composted is a major determination of the rate of the composting process (Clark, 1977). At 30 h however, (the time treatments were imposed upon reactors in R8), no significant differences were found between compost temperatures for R6 and R7 ($p > 0.05$).

Concern was raised over the fact that the lengths of time over which thermophilic temperatures were maintained for all three experiments were slightly shorter than that typically reported in literature. One obvious reason for constraint in decomposition was the lack of moisture near the bottom and sides of the composting chamber. Iwabuchi *et al.*, (1995) composted two different straw-manure mixtures with moisture contents of 31.4% and 76.7% using air flow rates of 40 and 56 L·(kgDM)$^{-1}$·h^{-1} respectively. After reaching thermophilic conditions, the batch with the lower moisture content started to decrease in temperature at 30 h, while the temperatures in the latter batch dropped at 60 h. Although final moisture contents reported (Table 5.3) for runs R6, R7, and R8 were not inhibiting, these values were measured from representative samples taken after mixing the final product. It was discovered, however, that the moisture content was a limiting factor for microbial activity. After each experimental run, the compost was always dry near the bottom and up along the sides of the reactor due to increased movement of air in these areas. This lack of moisture not only inhibited the metabolism and activity of microorganisms, but also decreased the compost's bulk volume of moist material, and thus the compost's ability to store heat. A decrease in the ability to store heat resulted in an early shift to the right in the heat balance (equation 3.3), thereby losing heat at a quicker rate than that being released from the catabolic activity of the microorganisms.

Another concern was raised over the varying durations in time of each study. Mean length of time for the compost temperature to peak and fall to 35°C for all vessels in R6 was 80.4 h, in R7 97.2 h (omitting vessel one), and in R8 113.5 h. As the rate of ventilating air (Table 5.2) was the only significantly different measured variable to potentially have an effect on the length of all three runs, it can be shown that the length in time of decomposition is related to the rate of air flow. A high rate of air flow translates to a high rate of moisture removal, thus moisture content becoming the limiting factor. This has also been verified in a report by MacGregor *et al.*, (1981), who stated that by increasing the air flow rate, more heat will be removed, and potentially decrease compost temperatures.

The excess air flow and limiting characteristics of deficient moisture content are also supported by the temperature curve for vessel one in R7 (Figure 5.6). During the initial rise in temperature, vessel one sustained a small leak in the plenum, thereby continuously allowing water from the water bath to feed into the bottom of the composter. Because of this, the mean air flow rate for the vessel was decreased to 44 $L\cdot(kgDM)^{-1}\cdot h^{-1}$, while the remaining five vessels were delivered an average of 119 $L\cdot(kgDM)^{-1}\cdot h^{-1}$ of air. As air flow and moisture content were the only varying parameters for vessel one, it was assumed that the low rate of air flow and the extra moisture added to the substrate was enough to maintain thermophilic temperatures in vessel one to 150 h. All other vessels descended from thermophilic temperatures at 90 h.

One solution to decrease moisture loss would have been to saturate the inlet air. This would have decreased the water vapor gradient between the gas Phase of the compost and the ventilating air. However, because air for two of the treatments in R8 was to be drawn from the coldroom at temperatures below zero, it was not possible to saturate the inlet air flow. Another option in avoiding high rates of evaporation would have been to decrease the rate of air flow. However, to fulfill air flow requirements of the three gas analyzers and to accurately measure gas concentrations, flow rates were needed to be greater than 0.5 $L\cdot min^{-1}$.

Table 5.2 shows the mean flow rates used in each experiment. The applied rates were higher than ones used by other researchers (Hogan *et al.*, 1989; Bach *et al.*, 1987; Ashbolt and Line, 1982), and this is reflected in the shorter lengths of time for each run. Most composting trials reported times of activation slightly longer than those recorded for R6, R7 and R8. The total length of time for the compost to peak and return to ambient temperatures for R6 was approximately 100h, while R7 and R8 lasted longer at 160 h each. However, most researchers, as the optimization of the composting process would suggest, saturated inlet air to reduce the water vapor gradient (Hogan *et al.*, 1989; Sikora and Sowers 1985; Ashbolt and Line, 1982; Carlyle and Norman, 1941). This was not possible here due to the nature of the study, and as already suggested, the increased water vapor gradient played an important role in limiting microbial activity. Bach *et al.*, (1987) used an air flow rate of 8 $L\cdot(kgDM)^{-1}\cdot h^{-1}$ in one study in composting sewage sludge and reported microbial activity lasting over 250 hours. Whether saturated inlet air was used in the study was not made clear. Ashbolt and Line, (1982) used 16 $L\cdot(kgDM)^{-1}\cdot h^{-1}$ and managed to maintain thermophilic conditions for 40 days. Although this was achieved through continuously mixing the substrate, pre-heating the air, and continuously returning moisture to the vessel. Hogan *et al.*, (1989) report two trials of composting rice hulls and flour to last only 225 h. In the experiment, pre-humidified air at 18°C was only delivered to the reactor as required based on a set temperature using a temperature feedback control. These authers claimed that operating the feedback control did inhibit and even decrease compost temperatures. In another experiment, Sikora and Sowers (1985), used temperature response aeration, and aerated at a rate of 900 to 1800 $L\cdot(kgDM)^{-1}\cdot h^{-1}$. These researchers also recorded a final moisture content of the compost of 33% and a length of compost runs of only 240 hours, even though they appear to have used pre-humidified air. Carlyle and Norman (1941) achieved just over 125 hours of activity in a 1.1 L adiabatic vessel supplied with pre-humidified and pre-heated inlet air.

It appears many experimental procedures cited used not only pre-humidified air, but pre-heated air as well. Increased sensible and latent energy entering the compost could potentially decrease the amount of energy removed through the exhaust, thereby requiring a greater air flow rate to retrieve the remaining heat. This would suggest that composting in a dry and cold environment would require very little ventilating air. This is supported by recent work done by Lynch and Cherry (1996), who experimented with composting windrows of manure/straw mixtures during winter. Initially, the researchers plugged the air pipes on two of the freshly built windrows. Once thermophilic conditions were achieved, (in which the unplugged pile was the slowest) plugs were removed and air was supplied to the core of the windrow solely through free convection. No aeration equipment was required. Composting in warmer environments require windrows to be aerated with air blowers and fans (McGregor *et al.*, 1981).

The temperature curves for the three treatments in R8 follow a pattern. Yet because R6 and R7 exhibit randomness amongst temperature curves, caution should be taken in assuming these trends to have emerged due to the varying temperatures in aerating air. However, the experimental variable in R8 was ventilation temperature while all other initial variables a function of decomposition were held constant (i.e. moisture, mass, ventilation rates, C:N ratio)($p > 0.05$). Due to this, it can be speculated that any variations seen between the temperature curves were a function of the different treatments.

Temperatures measured in R8 and graphed in Figure 5.6 show that once peak temperatures were reached, compost vessels sharing the same treatment tended to behave similarly. Temperatures for the -5 (vessels five and six) and +5 (vessels two and four) treatments did not vary much from one another and in most times exhibited the same slope. Temperature gradients in the ambient treatment (vessels one and three) decreased rapidly shortly after peaking, but then followed the same slope as the other two treatments. This rapid decrease in temperature for the ambient treatment was evident in some of the vessels in R6 and R7. Optimal temperatures for heterotrophic thermophiles (55 to 60°C) were surpassed (Strom, 1985; McKinley and Vestal, 1985; Suler and Finstein, 1977; Wiley, 1957a), but, because of the high aeration rate, it is doubtful that this was the reason behind the quick drop in temperature. Rather, the ventilation system may have over compensated in removing heat.

Conductive losses may not have been negligible, yet thermodynamic analysis (Table 5.4) accounted for conductive fluxes, thus leaving only air temperature changes and vaporization as the mechanisms for heat removal.

Since latent heat of vaporization potentially accounts for 90% of the total heat loss (MacGregor *et al.*, 1981), it could be hypothesized that a higher rate of vaporization in certain regions of the compost matrix in the ambient treatment accounted for the quicker fall in temperature. This can be explained by the simple fact that air at 20°C has a higher water holding capacity than air at -5°C. The 20°C inlet air entering the vessel would potentially accumulate a larger amount of moisture from the initial layers of moist compost than air at -5°C. Decreasing the moisture content drastically in one part of the compost bulk volume, as would be expected to occur with the ambient treatment, reduces the effective active volume of compost. This would reduce the amount of degradation and the time of microbial activity. With air entering at -5°C however, the accumulation of water would take longer as the air slowly equilibrates with compost conditions. Moisture collected in the air of the -5 treatment would thus tend to be gathered from a larger volume of compost and have a less inhibiting effect on overall activity. This would explain the differences in the temperature curves between treatments in Figure 5.6, thus supporting the hypothesis of the study. Therefore it could be suggested that for cold climate composting applications where thermophilic temperatures have already been achieved, ventilating with warm air is not necessary.

As the data in Phase I had also suggested, this would further mean that composting in a dry and cold environment would require very low rates of ventilating air, and that proper gas exchange would be the more important operational parameter. This is supported by recent work done by Lynch and Cherry (1996)(section 4.5), who experimented with passively aerated windrows of manure/straw compost mixtures during winter. It was concluded that respiratory gas diffusivity (i.e. supply of O_2 and removal of CO_2) was the primary governing control function for the cold climate composting process, as opposed to heat removal for composting in warmer environments.

The mean final moisture contents tabulated in Table 5.3 support this explanation. Ambient treatments finished with a slightly lower value of 71.5%, while +5 and -5 ended with 76.1% and 75.4% respectively. It is important to remember that these recorded values for moisture were representative of the entire compost mass within the vessel, but varied greatly within the compost matrix.

However, because of the small range in moisture contents and the nonhomogeneous moisture distribution during sampling, it is difficult to suggest that an increased rate of vaporization was the cause of the rapid decrease in compost temperatures. Rather, this implies that a nonuniform rate of vaporization was applied to the entire compost matrix.

In view of this, the temperature plots for R8 oppose the hypothesis of low ventilation temperatures decreasing the activity of composting microorganisms. Rather, the cold inlet air tended to increase the rate of degradation.

5.5.3. Heat production

Little to no work has been reported in the area of varying compost inlet air temperatures, making it difficult to compare measured values of heat production from R8 with other studies. However, the amounts of heat produced per mass composted for all three experiments (Table 5.4) yielded values very similar to those reported in the literature. Mean heat output per unit mass of dry matter lost for treatments -5, +5°C, and ambient were 25.5, 21.0, and 22.0 $kJ(g{\cdot}DM)^{-1}$ respectively, while the peak for R6 was 18.6 $kJ(g{\cdot}DM)^{-1}$ and R7 14.8 $kJ(g{\cdot}DM)^{-1}$. As the mean values show, little differences can be noted between values for R6, R7, and R8. Miller (1984) reported averages of 21.8 and 15.2 $kJ(g{\cdot}DM)^{-1}$ from composting sewage sludge while Finstein *et al.*, (1986), using the same adiabatic system, calculated 13.1 kJ(g·DM)$^{-1}$ in the degradation of oak leaves. Bach *et al.* (1987) reported a calculated heat output of only 2.5 kJ(g·DM)$^{-1}$. Miller *et al.*, (1989), measured heat outputs of 8.4, 31.4, and 37.7 kJ(g·DM)$^{-1}$ when composting mushrooms with straw at temperatures of 72, 55, and 45°C. This trend of a decreased heat output with increased temperatures was also verified by Rothbaum (1961). Unfortunately, this trend cannot be applied here, as these values pertained to mean compost temperatures measured under isothermal conditions, and as was discussed earlier, treatments had little or no effect on compost temperature.

The only significant differences between treatments at the five percent level was the rate of heat produced during peak temperatures (Table 5.5 and Figure 5.22). The -5 treatment from 30 h to 60 h had a significantly higher rate of thermal energy production in comparison to the +5 and ambient treatments as plotted in Figure 5.14. However, this analysis should be considered with caution. Vessel six, one of the two replicates in the -5 treatment, exhibited a very high rate of heat evolution during peak temperatures (peak heat output of 43 W) while the other replicate (vessel five) showed little increase (Figure 5.20 and 5.21) in the rate of heat production. This had an effect on the statistical test. Nonetheless, both vessels in the -5 treatment did have the highest peak rates of heat output, 37 and 43 W from vessels five and six respectively, out of the three treatments, as well as runs R6 and R7. Also, by integrating the average rates of heat output, vessel six still yielded the highest total heat output, and the heat output in vessel five was greater than any of the values measured in the ambient treatment. Although values were not significantly different between treatments, this does hint at the possibility of higher rates of microbial activity to have occured in vessels five and six, during thermophilic temperatures, due to the colder inlet air.

Table 5.4 presents the discrepencies in measured heat production between treatments with R8 more clearly. No significant differences at the five percent level were measured between most of the data presented in Table 5.4 on R8, yet differences were detected at the ten percent level. The peak rate of heat produced (as shown in Table 5.5) and the heat produced per unit mass of VDM composted in the -5 treatment were both significantly greater in the ambient treatment ($p < 0.10$). The +5 treatment was not significanly different from either the -5 or the ambient treatment. All other variables in Table 5.4 were not significantly different at the ten percent level. On the basis of the peak rate of heat produced as mentioned earlier, this does suggest that the different treatments did have an effect on the amount of thermal energy being produced. The compost receiving colder air exhibited higher rates of activity through increased heat production. It could be argued that the validity of this is uncertain as some heat production data between treatments does not agree with this claim. For example, vessel three, one of the replicates for the ambient treatment, actually achieved the greatest amount of heat produced per dry mass of material lost. As well, a replicate of the +5 treatment lost the most DM as opposed to all other vessels. Unfortunately though, these opposing arguments need to be viewed with caution as these values include a margin of error contributed by the uncertainty in final moisture contents.

The highest measured value of heat output in R8 occurred in the -5 treatment during thermophilic conditions as discussed above (also seen in Figure 5.22). Therefore, during peak temperatures, these vessels (numbers five and six) produced more heat per available substrate than the compost in the vessels of the other two treatments. This can be explained in several ways. First, because of the large temperature differential between the inlet air and the compost, the rate of heat removal was the highest for the -5 treatment. This is supported by the fact that the temperature curves for the -5 and +5 treatment are very similar. Expanding this reasoning further, an increased rate of heat removal could likewise be related to an increase in degradation.

The first assumption assumes that the rate of heat loss was greater in the -5 treatment than in the +5 and ambient treatment. The final moisture content, including error, was high, and suggests that sensible heat loss may have been a greater factor in heat removal for the -5 treatment. This can be verified, as the difference in temperature between the air and compost for the -5 treatment was 25°C greater than the ambient treatment. This is equivalent to a 25 kJ·(kg dry air)$^{-1}$ (C_p = 1.005 kJ·kg^{-1}·°C^{-1}) increase in heat removal. As well, because the humidity ratio of the air entering into the composters from the coldroom did not change between treatments, all vessels received equal amounts of moisture via ventilation. Exhaust was assumed saturated at compost temperature, thereby allowing no variations in the amount of water lost between vessels *if* compost temperatures were equal. However, vessels one and three (ambient treatment) lasted the shortest length of time (Table 5.3) and maintained lower temperatures (Figure 5.7) than the compost of the other two treatments. This would lead to a decrease in total heat output in the ambient treatment as temperature is a direct function of latent heat of vaporization (equation 3.12). Although not significantly different ($p<0.05$), Table 5.4 shows that vessels one and three did have the lowest accumulated heat outputs. The mean total heat output for the ambient treatment, (not shown in Table 5.4), was the lowest at 1371 kJ, while the -5 and + 5 treatments accumulated 2249 and 1700 kJ respectively. From this it could be assumed that the rate of heat removal in the -5 treatment was greater than the other two treatments, and opposes the hypothesis for Phase II.

The explanation above also points to an increase in the amount of volatile solids lost because of an increase in the rate of degradation. This is difficult to validate due to possible discrepencies in total DM lost. However, assuming a constant discrepency, this explanation is still not wholly apparent. The vessels receiving the -5 treatment lost a mean mass of 91 grams. and the +5 and ambient lost 89.5 and 88.5 grams. A one or two gram difference between treatments, translated to approximately 0.2% of the mean initial dry mass, can be argued as error.

The largest discrepancies between measured values from all three experimental studies, and of those in literature, were the maximum rates of heat production in respect to initial VDM ($J \cdot g(VDM)^{-1} \cdot h^{-1}$)[5] . The mean evolution of heat in respect to the initial dry starting mass per vessel were 164.5, 211.0, and 364 $J \cdot (gDM)^{-1} \cdot h^{-1}$ for treatments ambient, +5 and -5 respectively, while R6 was 171 $J \cdot (gDM)^{-1} \cdot h^{-1}$ and R7 measured 119.6. $J \cdot (gDM)^{-1} \cdot h^{-1}$. In the literature, Mote and Griffis (1982) reported one of the highest values of 100 $J \cdot (gDM)^{-1} \cdot h^{-1}$ while composting cotton gin trash. Wiley (1957) calculated 76.7 $J \cdot (gDM)^{-1} \cdot h^{-1}$, also quite high, as most cited values range from 8.4 $J \cdot (gDM)^{-1} \cdot h^{-1}$ (Miller *et al.* 1989) to 48.2 $J \cdot (gDM)^{-1} \cdot h^{-1}$ by Carlyle and Norman (1941). Why the peak rate of heat production per unit mass of initial DM were so high, compared to typical, is difficult to explain due to the lack of data.

A large amount of DM lost over the shorter than typical active period could have indicated higher rates of heat released per mass of initial DM.

If the amount of water produced per unit mass lost were known, it would also aid in explaining the high peak rates of heat production per initial DM. A large amount of water produced per DM lost could indicate a greater amount of energy released due to a larger percentage of fatty acids present. Fatty acids release large amounts of water and both thermal and chemical energy due to the large molecule sizes (Franke, 1996).

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[5] Values for peak rates of heat production per initial VDM and DM were calculated by dividing the maximum rate of heat production during every experiment for every vessel by the initial DM of the material composted.

High values of water lost per mass of dry matter of compost disappearing could have been due not to microbial induced biochemical reactions, but rather from alternative mechanisms. The high air flow rate used could have been a contributing factor in removing the excess moisture. Drying and destruction of VS have been reported to be highest with high aeration rates (Kuter *et al.*, 1985; Sikora and Sowers, 1985). This would also explain the high values obtained for the maximum rate of heat evolved. The maximum rate of heat produced was measured during high compost temperatures, or thermophilic conditions. The increased temperature in air, working in conjunction with the high rate of air flow, would lead to high rates of vaporization, and thus high rates of latent heat loss. This is not reflected by the heat evolved per dry matter lost as peak temperatures were not maintained for a very long time (Figures 5.4, 5.5, and 5.6). Most curves show that temperatures decreased soon after a maximum was reached.

Differences in heat content measured using bomb calorimetry and enthalpy in R7 and R8 were insignificant. The amount of heat retrieved from most of the dried compost samples were slightly less than those values calculated during the studies. These differences can be explained. An oxidized substrate undergoes a complex biochemical path of events, ultimately producing products of combustion, chemical energy in different complex forms (i.e. enzymes such as adenine triphosphate, or ATP), and thermal energy. Battley (1987) supports this by saying that metabolic activity always allows some energy to be lost as heat. Part of the chemical energy is then either recycled during the further catabolism of organic cells or consumed in anabolism. These operations in turn release more heat. These ongoing microbial induced biochemical reactions allow for the production of heat at varying rates independent of the substrate's heat of combustion.

5.5.4. Gas analysis

As in Phase I, the shapes of the curves for the cumulative O_2 consumed and CO_2 produced during all three experimental studies were very similar (Figures 5.7 and 5.12). This was expected, as CO_2 evolving from cell metabolism must reflect the amount of O_2 consumed for respiration. Each CO_2 and O_2 plot also related well to the temperature dynamics of the three treatments. Higher rates of CO_2 emission and O_2 consumption were evident during periods when temperatures were at maximum values of 50 to 60°C. This has also been verified in studies by Jeris and Regan (1973), and Suler and Finstein (1977) who both report maximum CO_2 outputs between 55 and 60°C. The notable decrease in respiration in all vessels in R7 is reflected in the low amounts of total heat produced (Table 5.4).

Most of the vessels in each run exhibited oxygen and carbon dioxide curves containing two peaks in the first 50 h. Even within the three treatments of R8 definite two-peak curves can be distinguished. Many researchers have experienced several peaks in respiratory gas exchange (Sikora *et al.*, 1983; Ashbolt and Line, 1982; Bowls, 1951), yet these have tended to occur a significant number of days after initiation and should not be compared to initial peaks (Miller, 1984), such as the peaks in Figures 5.7 to 5.12. Data reported by Carlyle and Norman (1941), according to Miller (1984), can be related to data collected here, as these researchers experienced a second peak in CO_2 at 60°C and approximately 50 h. Atkinson *et al.*, (1996) report the same occurrence while composting municipal solid wastes with a second peak in CO_2 production measured within the first 100 h. Initial assumptions related the two peaks in response to transitions in mesophilic and thermophilic activity (Carlyle and Norman, 1941; Sikora *et al.*, 1983; Atkinson *et al.*, 1996). However Atkinson *et al.*, (1996) lists several other possible explanations contributed by other researchers. Greer *et al.*, (1990) and Fogarty and Tuovinen (1991) support the assumption that the changes in CO_2 evolution are due to changes in active microbial populations. Other reasons included changes in enzymatic activity (Diaz-Raviña *et al.*, 1989), variances in moisture content (Ciavatta *et al.*, 1993; Hall *et al.*, 1993; Haug 1993), or sudden exposure to available substrate (Riffaldi *et al.*, 1992). Although these theories were conceived to elucidate gas exchange in experiments dealing with the composting of municipal solid wastes, some applicability to manure composting could be made safely. Peaks in the amount of CO_2 produced are also noticeable in all three treatments of R8 and, therefore it can be assumed that the different treatments had no effect on this characteristic.

Although differences in all gas exchanges for run R8 were insignificant, Table 5.1 shows that the vessels receiving the +5°C air had the highest rate of respiration. While vessels receiving ambient air utilized and released the least O_2 and CO_2 respectively, yet produced the most NH_3 gas. Vessels two and four (treatment +5) may have produced the same amount of NH_3, if not more, in view of the standard deviation for that treatment.

The large concentrations of O_2 consumed and CO_2 released in R6 are reflected by the high amounts of thermal energy produced and DM lost. This is in contrast to R7, with low amounts of respiratory gas exchange and DM lost. The mean heat output per unit mass of DM lost was 18.6 $kJ\cdot(gDM)^{-1}$ in R6, but only 14.8 $kJ\cdot(gDM)^{-1}$ in R7, while mean DM losses were 127.2 and 92.8 grams DM for R6 and R7 respectively. Surprisingly though, R6 ran for a shorter length of time than R7. Thus, the rate of degradation in R6 seems to have been much greater than in R7. The question remaining is: what factors influenced the metabolic rate to provide a quicker rate of decomposition in R6 than in R7? Differences in initial dry mass, wet mass, moisture content, and C:N ratio were insignificant between R6 and R7. The mean rate of air flow in R6 was tested to be significantly greater than R7, but as previously discussed, this would have potentially deterred microbial activity. The amounts of ammonia released in both runs was also significantly different.

The high degree of error in measuring O_2 and CO_2 concentrations makes it difficult to draw conclusions based on differences in respiratory gas concentrations. This is underlined by the high values of standard deviations shown in Table 5.1.

The peaks in NH_3 production in Figures 5.20, 5.21, and 5.22 mimick those of Phase I. As discussed in section 4.5.2., the reasons for the typical high release in N during the onset of high compost temperatures is not certain. Janzen *et al.*, (in preparation, b) suggests the peak NH_3 emmisions result from the inbalance in the $NH_4^+ \leftrightarrow NH_3$ equilibrium due to increased temperature-dependent ventilation rates during peak temperatures. In support of this, they further go on to point out that Waksman *et al.*. (1939) reported the highest N retention documented in the absence of forced ventilation. Although ventilation in Phase II was not temperature-dependent, R6 did receive a significantly higher rate of air than R7, and produced significantly more ammonia. However, as ventilation was constant, this does not explain the short burst of NH_3 release during the initial temperature rise. Several explanations can be made from this. First, an increase in mineralization of N , because of an initial excessive amount of N, may have occured which led to an abundance of NH_4^+ , and therefore an increase in NH_3. Or secondly, a rise in pH occured, driving the $NH_4^+ \leftrightarrow NH_3$ equilibrium to the right, as release of N is a function of increased pH (Miller, 1993; Koster, 1986; Lauer *et al.*, 1973).

Differences in amounts of ammonia released between treatments in R8 were insignificantly small, and, as the NH_3 analyzer had very small error in readings, it can be safely assumed that the different inlet temperatures for each treatment in R8 were not a function of the rates of N release.

5.5.5. Theoretical heat analysis

To aid in the quantitative analysis of the effect of cold aeration temperatures on heat evolution. the amount of heat released was predicted by the oxygen uptake rates using two different stoichiometric models. The first was derived by Finstein *et al.*, (1986) and estimated that 14 000 kJ of heat would be released per kilogram O_2 consumed. The second model was derived on the basis of the combustion of total available carbohydrates, proteins and fatty acids (Franke, 1996). This estimated that 430 kJ would be released per mole of O_2 consumed or, in terms of mass, 13 450 $kJ \cdot kgO_2^{-1}$ consumed[6] . Both models assumed complete oxidation of organic matter. Values derived by these two models were assumed to be valid because the O_2 concentrations that were measured were sufficient to not inhibit metabolism at any time during each run.

Table 5.7 compares the measured values obtained in this study for total heat output and heat output per DM lost with those derived by Finstein *et al.*, (1986) and Franke (1996).

Statistically (p=0.05), no differences were detected between all three methods (i.e. measured, Finstein *et al.*, (1986), and Franke (1996)) in R6 and R7. Also, in R8, differences between the methods and the methods within each treatment were both insignificant.

On the basis of cumulative values[7] , statistically, the different treatments did not increase nor decrease the amount of heat produced. Although, values for heat output and heat

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[6] Calculated according to recommended ratios of 80, 20, and 10% carbohydrates, proteins, and fatty acids respectively in a typical manure/straw solid waste compost pile (Franke, 1996). The stoichiometric model defined by Franke (1996), was derived on the basis of the nonconservative combustion of one mole of glucose ($C_6H_{12}O_6$), lysine ($C_6H_{14}N_2O_2$), and palmitic acid ($C_{16}H_{32}O_2$). Each representing a carbohydrate, protein, and fatty acid constituent respectively.

[7] The rate of heat produced (W) exhibited significant differences between treatments (Table 5.5) during thermophilic temperatures, while total heat output and heat output per DM and VDM lost did not.

TABLE 5.7 COMPARISON OF TOTAL HEATS

Experimental run	Measured Heat Output [kJ]	Heat Output according to Finstein *et al.* (1986) [kJ]	Heat Output according to Franke (1997) [kJ]	Measured Heat Output per DM lost [kJ·(gDM)$^{-1}$]	Heat Output per DM lost according to Finstein *et al.* (1986) [kJ·(gDM)$^{-1}$]	Heat Output per DM lost according to Franke (1997) [kJ·(gDM)$^{-1}$]
R6-1	2631	3064	2941	21	25	24
R6-2	-	-	-	-	-	-
R6-3	3054	1954	1876	20	13	12
R6-4	2869	3108	2983	13	15	14
R6-5	1627	1280	1228	14	11	11
R6-6	2466	3285	3153	25	34	32
R7-1	1371	1173	1126	9	8	7
R7-2	1384	1064	1021	8	6	6
R7-3	1357	909	873	20	14	13
R7-4	1176	1132	1086	18	18	17
R7-5	1470	841	807	11	6	6
R7-6	1072	1016	976	17	16	15
R8(a)-1	1020	963	925	14	13	12
R8(a)-3	1722	1002	962	30	18	17
R8(+5)-2	1338	1574	1511	24	29	28
R8(+5)-4	2061	1618	1552	18	14	13
R8(-5)-5	1843	1187	1139	22	14	13
R8(-5)-6	2654	1660	1593	29	18	17

output per DM lost for both stoichiometric models do hint again of differences, as discussed with the measured values in section 5.5.3. For example, the cumulative heat produced in the ambient treatment predicted by Finstein *et al.*, (1986), and Franke (1996), did produce less heat as opposed to the -5 and +5 treatment (Table 5.7).

The validity of these models in comparison to measured values may, however, be questionable, as some inconsistencies exist between methods of analysis. For example, the highest heat output per mass of DM lost calculated through stoichiometry, occurred in the +5 treatment (vessel two). This is inconsistent with amounts measured previously, which yield the ambient and the -5 treatments as producing the highest heat output per DM lost. Inconsistencies between methods of thermal analysis could be contributed to errors relating to dry matter and moisture content measurements.

5.6. Phase II Conclusion

Phase II experimental studies R6 and R7 assured that the repeatability and procedure of the experimental system was adequate to test the hypothesis in R8. The design objective to minimize all conductive heat flow from the composting chamber was not entirely fulfilled. Nonetheless, total heat outputs were compensated accordingly.

The lengths of time over which thermophilic temperatures were maintained for all three experiments were slightly shorter than that typically reported in literature. This was attributed to a high removal rate of moisture from the compost. Although final moisture contents reported (Table 5.3) for runs R6, R7, and R8 were high, true representative samples were difficult to collect because of the large moisture gradients in the final product. High rates of moisture loss was evident in all vessels, yet to a lesser degree in the four receiving the +5 and -5 treatments in R8. Since latent heat of vaporization in the ventilating air can potentially account for 90% of the total heat loss (MacGregor *et al.*, 1981), it could be hypothesized that a higher rate of vaporization in certain regions of the compost matrix in the ambient treatment accounted for the quicker fall in temperature. This explanation would account for possible variations in the rates of activity between treatments reflected by the differences in the temperature curves (Figure 5.6). Unfortunately, these conclusions state that the -5 treatment produced the most heat in respect to the +5 and ambient treatments, which contradicts the hypothesis of the Phase II study.

The only significant difference found between treatments at the five percent level was the rate of heat produced during peak temperatures (Table 5.5 and Figure 5.13), in which the

-5 treatment had a significantly higher rate of heat output in respect to the +5 and ambient treatments. The mechanisms providing the increased rate of microbial activity in the -5 treatment were possibly due to either a higher rate of heat removal, a decreased rate of moisture loss, or a nonuniform removal of water. Inversely, all three can be related to the decreased active area in the compost of the ambient treatment, as discussed earlier. While lower rates of activity in the ambient treatment are supported by the shorter length of time (Table 5.3), lower temperatures (Figure 5.7), and the low accumulated heat outputs (Table 5.4). These parameters surrounding the rates of activity would suggest that full-scale composting in a dry and cold environment would require very low rates of ventilating air, and that proper gas exchange to be the more important operational parameter.

Maximum rates of heat production in respect to initial VDM ($J \cdot g(VDM)^{-1} \cdot h^{-1}$) in all vessels in each run were found to be high compared to those in the literature. This was difficult to explain due to the lack of data. However, a large amount of DM lost over the shorter than typical active period could have indicated higher rates of heat were released per mass of initial DM. As well, a large amount of water produced per DM lost could have indicated a greater amount of energy was released due to a larger percentage of fatty acids present. High values of water lost per dry matter of compost disappearing could alternatively have explained large amount of excess moisture being displaced due to the high air flow rates used. The increased temperature in air, working in conjunction with the high rate of air flow provided high rates of vaporization and would have led to high rates of latent heat loss (i.e. high heat production in respect to initial VDM). This may not have been reflected upon the heat evolved per dry matter lost ($kJ \cdot (gDM)^{-1}$ as peak temperatures were not maintained for a very long time (Figures 5.4, 5.5, and 5.6).

In addition to the measured values, two stoichiometric models (Finstein *et al.*, 1986 and Franke, 1996) and bomb calorimetry[8] were used to predict the amount of heat released per vessel in R6 and R7, and to test the hypothesis in the treatments in R8. Statistically ($p=0.05$), no differences were detected between the two models, bomb calorimetry, and the measured values in R6, R7, and R8. Also, as seen with the measured values in R8, no significant differences were found in the values predicted by the models and of those measured through bomb calorimetry between treatments. However, values in R8 for heat output for both models do again hint at increased heat outputs in the -5 treatment, as seen with the measured values, thereby again suggesting that the colder inlet air did increase the rate of heat output from the compost. This again contradicts the hypothesis of the Phase II study which stated that the continuous flow of cold air would actually decrease, rather than increase, the rate of microbial activity. From this it could be suggested that for cold climate composting applications, ventilating with warm air is not necessary if the compost exhibits thermophilic conditions.

Each CO_2 and O_2 plot related well to the temperature dynamics of the three treatments. Higher rates of CO_2 emission and O_2 consumption were evident during periods when temperatures were at maximum values of 50 to 60°C.

Each run exhibited oxygen and carbon dioxide curves containing two peaks in the first 50 h. Similar peaks in the amount of CO_2 produced were also noticeable in all three treatments of R8 and, therefore, it can be assumed that the different treatments had no effect on this characteristic.

Differences in all gas exchanges between treatments for run R8 were found to be insignificantly different.

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[8] Bomb calorimetry was only performed on samples from R7 and R8.

The rate of degradation may have been greater in R6 than that in R7. This is supported by the large concentrations of O_2 consumed and CO_2 released, the high amounts of thermal energy produced, and shorter length of time in R6. In contrast, R7 had low amounts of respiratory gas exchange and longer times of activity. Yet, due to the high degree of error in measuring O_2 and CO_2 concentrations, it is difficult to draw conclusions based on differences in respiratory gas concentrations.

The peaks in NH_3 production in Figures 5.20, 5.21, and 5.22 mimick those of Phase I. Reasons for the typical high release in N during the onset of high compost temperatures is not certain (Janzen *et al.*, in preparation, b). Nonetheless, differences in amounts of ammonia released between treatments in R8 were insignificantly small, and, as the NH_3 analyzer had very small error in readings, it can be safely assumed that the rates of N released were not a function of the different inlet temperatures.

5.7. Phase II Recommendations

Several alterations in the composting design system would have helped to optimize the composting process and improve the accuracy of several of the required quanitative properties of the process.

The installation of horizontal vanes or baffles on the inside bottom of each laboratory scale reactor would have detered the flow of air from traveling up along the sides of the vessel and have forced more air to infiltrate through the compost matrix. The quantity of moisture lost near the bottom and sides of the vessel would have decreased, and provided a more homogeneous water content throughout the entire bulk of the compost. This would have also increased the accuracy of the final moisture contents due to better representative sampling.

Conductive losses in laboratory-scale models are important and need to be addressed seriously. Despite typical maximum temperature gradients of 2.5°C (Figure 3.1) between the compost and the water bath, significant fluxes of conductive heat were analyzed in some of the vessels. In order to accurately similate large-scale applications in a laboratory-scale model, conductive fluxes have to be eliminated (Hogan *et al.*, 1989). The large amounts of conductive heat flows also contradicted the already-stretched definition of an adiabatic composting system. Most difficulties in maintaining equal temperatures were experienced during thermophilic temperature and during the decline in temperatures. The large amount of thermal energy that needed to be controlled at peak temperatures made it difficult for the water bath to keep up with the compost. Possibly a larger immersion element would be needed, in addition to insulating the entire bath. However, this insulation would need to be removed while the compost temperature decreased. During this stage of the composting process, the rate of heat lost from the composter, because of the ventilation rate, was in most cases greater than the rate of heat lost from the water bath. The installation of a heat exchanger may have eliminated this problem.

6. Conclusions and Applications

The Phase I study verified that low ventilation and ambient temperatures decrease the overall heat balance (equation 3.1) and decrease the amount of microbial activity in the compost. This was exemplified by the warm-warm vessels which maintained thermophilic temperatures well after 200h, while the warm-cold and cold-cold vessels decreased in temperature after 150h. As well, the mean RQ value for the warm-warm vessels was 0.97 in respect to the lower RQ values of the warm-cold and cold-cold vessels of 0.90 and 0.89 respectively. The cold ambient temperatures undoubtedly played the biggest role, as little differences were detected between the warm-cold and cold-cold treatments.

In Phase II, although the low ventilating air temperatures were statistically found to not have decreased (or increased) the rate of microbial activity, values for temperature and heat output suggest that the cold ventilating air alone had an impact on heat removal and moisture content, both a factor of activity. Mean heat output per unit mass of dry matter lost for treatments -5, +5, and ambient were 25.5, 21.0, and 22.0 $kJ\cdot(gDM)^{-1}$ respectively, while temperature gradients for R8 show that compost temperatures in the ambient treatment decreased first, as opposed to the +5 and -5 treatments. Values measured and plotted implied that the colder inlet air either increased microbial metabolism or increased the length of time of activity, both contrary to the Phase II hypothesis.

The differences in Phase I and Phase II are in the amounts of conductive heat lost during each experiment. Conductive losses were greater than expected in both Phase I and Phase II, and the Phase II system did lose heat through conduction. Yet, because of the obvious differences in temperature gradients between the compost temperature and the temperature of the surrounding medium of Phase I and Phase II, the Phase II system did represent a more accurate system of study. And in Phase II it was discovered that the more important mechanism of heat removal was found to be through latent and sensible heat loss.

Therefore, in cold climate composting if conductive losses are kept to a minimum (i.e. the core of a large compost pile), heat will be removed through uniform vaporization if ventilated with cold air. This assumes that the moisture does not become trapped at the colder perimeter of the compost pile. This is opposed to nonuniform vaporization that may occur if ventilating with warm air into a large compost heap in a cold environment. Data from Phase II points to this fact. Therefore it could be suggested that for cold climate composting applications, ventilating with warm air is not necessary if the compost is already exhibiting thermophilic temperatures

The Phase I and Phase II results can be integrated and applied to a full-scale composting process. Large amounst of conductive heat will be lost in a compost pile. In warm climate composting, conduction is insignificant, but obviously this changes for composting in colder climates. Ventilation rates, and therefore costs, can be reduced. Heat removal will not be dependent on ventilation. Since aeration serves both to provide O_2 and to remove excess heat (Shulze, 1965), the most important control parameter would be to provide sufficient respiratory gas exchange. Findings by Suler and Finstein (1977) suggested that 10% O_2 residual is adequate for metabolism. In Phase I and Phase II oxygen levels remained well above the 10% residual concentration, including error, however the ventilation rates used were quite high.

These conclusions are partly supported by recent work done by Lynch and Cherry (1996), who experimented with composting windrows of manure/straw mixtures during winter. Initially, the researchers plugged the air pipes on two of the freshly built windrows. Once thermophilic conditions were achieved (in which the unplugged pile was the slowest), plugs were removed and air was supplied to the core of the windrow solely through free convection. No aeration equipment was required. Oxygen concentrations were reported below 10% near the middle and top of the pile. This may have resulted from the decrease of O_2 solubility at the higher temperatures at the core of the pile. However, because of the low O_2 concentrations near the perimeter of the pile and the absence of ventilating fans, undoubtedly there was insufficient positive pressure to disperse air through the entire pile, and through the frozen insulative layer of compost on the perimeter of the pile.

The few works done on cold climate composting, along with the results presented here, are more than adequate to show that composting in a colder and dryer environment is not only possible, but viable as well. The lack of comparative data in cold climate composting itself suggests that, to understand the thermodynamic principles and dynamics involved in the cold climate composting process, further study is recommended. As pointed out, different operational parameters pertain to cold climate composting. Optimizing the entire process requires these individual parameters to be magnified and the dynamics exposed. Not until every individual function and parameter of the composting process is completely understood, will the knowledge to completely optimize the cold climate composting process be available.

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9. Appendix

Statistical programs used in the Phase II study.

i) Statisical Analysis: Comparison of measured values for R6 and R7

```
options linesize=96 pagesize=70 formdlim='-';
data test;
        input exper $ ttlheat peakW avgW DMlst VDMlst kJDMlst JintlVDM  time @@;
        cards;
        r6 2631 19.9 10.4 123 114 21 155 81
        r6 .   .    .  .    .  .  .   .
        r6 3054 24.7 11.4 155 140 20 208 86
        r6 2869 23.6 11.3 214 188 13 164 81
        r6 1627 12 7.2 114 102 14 98 74
        r6 2466 28.3 9.8 97 92 25 230 80
        r7 .  .    .  .  .  .  .  .
        r7 1384 15.7 4.1 167 152 8 125 103
        r7 1357 15 3.9 67 63 20 119 105
        r7 1176 14.9 4.3 65 66 18 113 86
        r7 1470 16 4.8 131 122 11 131 94
        r7 1072 13.7 3.4 65 61 17 110 98
proc print;
        title 'Measured heats and mass lost';
        title2 'runs 6 and 7';
proc glm;
        class exper;
        model ttlheat peakW avgW DMlst VDMlst kJDMlst JintlVDM time = exper;
        means exper / lsd duncan;
        lsmeans exper / stderr pdiff;
run;
```

ii) Statisical Analysis: Comparison of measured and predicted values for R6 and R7

```
options linesize=96 pagesize=70 formdlim='-';
data test;
        input exper $ oxy cd amm vent cond condper finstein franke @@;
        cards;
        r6 219 126 .38 2974 343 13 3064 2941
        r6 . . . . . . . .
        r6 140 31 .28 2957 -97 3 1954 1876
        r6 222 131 .46 2819 -49 2 3108 2983
        r6 91 9 .24 1679 52 3 1280 1228
        r6 235 123 .35 2452 -13 1 3285 3153
        r7 .  .    .  .  .  .  .  .
        r7 76 55 .18 1770 386 28 1064 1021
```

```
        r7 65 20 .16 1742 385 28 909 873
        r7 81 40 .16 1505 329 28 1132 1086
        r7 60 10 .14 1834 364 25 841 807
        r7 73 28 .12 1448 376 35 1016 976
proc print;
        title 'Measured gases and heats';
        title2 'Runs 6 and 7';
proc glm;
        class exper;
        model oxy cd amm vent cond condper finstein franke = exper;
        means exper / lsd duncan;
        means exper / lsd duncan alpha = 0.10;
        lsmeans exper / stderr pdiff;
run;
```

iii) Statisical Analysis: Comparison of measured ventilation parameters and initial masses for R6, R7 and R8

```
options linesize=96 pagesize=70 formdlim='-';
data test;
        input exper $ air airrcv airmass wmass dmass @@;
        cards;
        r6 2.02 8.72 225 2455 538
        r6 1.86 2.81 208 2408 535
        r6 1.89 8.39 227 2244 498
        r6 1.85 8.11 183 2726 605
        r6 1.83 7.27 216 2298 510
        r6 1.68 7.2  196 2318 515
        r7 .42  3.94 . 2563 561
        r7 .88  5.04 102 2372 519
        r7 .95  5.78 110 2376 520
        r7 1.06 5.25  117 2488 545
        r7 1.2  6.50 143 2310 506
        r7 1.07 5.5  125 2348 514
        r8 .88  4.55 115 2279 456
        r8 .65  4.2  81 2379 476
        r8 .77  3.82 98 2348 470
        r8 .75  4.69 96 2362 472
        r8 .76  4.3  100 2268 454
        r8 .66  4.63 88 2258 452
proc print;
        title 'Air flow, total air received, and initial wet and dry masses';
        title2 'Runs 6, 7, and 8';
proc glm;
        class exper;
        model air airrcv airmass wmass dmass= exper;
        means exper / lsd duncan;
        lsmeans exper / stderr pdiff;
```

```
run:
```

iv) Statisical Analysis: Comparison of measured and predicted heats and bomb calorimetry in R7

```
options linesize=96 pagesize=70 formdlim='-';
data test;
      input exper $ heat @@;
      cards;
      b7 16.57 b7 16.87 b7 16.49 b7 17.29 b7  17.13
      r7 8 r7 20 r7 18 r7 11 r7 17
      f7 6 f7 14 f7 18 f7 6 f7 16
      j7 6 j7 13 j7 17 j7 6 j7 15
proc print;
      title 'Comparing measured heats and bomb calorimetry';
proc glm;
      class exper;
      model heat = exper;
      means exper / lsd duncan;
      means exper / lsd duncan alpha = 0.1;
      lsmeans exper / stderr pdiff;
run;
```

v) Statisical Analysis: Comparison of measured and predicted heats and bomb calorimetry in R8

```
options linesize=96 pagesize=70 formdlim='-';
data test;
      input temp method vessel heat @@;
      cards;
      20 1 1 14
      20 1 2 30
      20 2 1 16.08
      20 2 2 15.91
      20 3 1 13
      20 3 2 18
      20 4 1 12
      20 4 2 17
      5 1 1 24
      5 1 2 18
      5 2 1 15.93
      5 2 2 15.59
      5 3 1 29
      5 3 2 14
      5 4 1 28
      5 4 2 13
      -5 1 1 22
      -5 1 2 29
```

```
        -5 2 1 15.83
        -5 2 2 15.61
        -5 3 1 14
        -5 3 2 18
        -5 4 1 13
        -5 4 2 17
proc print;
        title1 'Comparing methods of heats in R8';
        title2 '1=measured 2=bomb 3=Finstein 4=Franke';
proc glm;
        class temp method vessel;
        model heat = temp method method*temp vessel(temp);
        test h=temp e=vessel(temp);
        random temp vessel(temp)/test;
        lsmeans temp / stderr e=vessel(temp);
        lsmeans method temp*method /stderr;
run;
```

vi) Statisical Analysis: Comparison of measured values for R8

```
options linesize=96 pagesize=70 formdlim='-';
data test;
        input temp obs ttlheat peakW avgW DMlst VDMlst kJDMlst JintlVDM time @@;
        cards;
        20 1 1020 12.8 3.4 123 116 14 117 96
        20 2 1722 23.8 5.6 57 61 30 212 99
        5 1 1338 15.8 3.6 55 64 24 139 117
        5 2 2061 31.9 5.2 118 115 18 283 123
        -5 1 1843 36.5 5 84 84 22 337 116
        -5 2 2654 42.2 6.3 93 98 29 391 130
proc print;
        title 'Measured heats and masses lost';
        title2 'Run 8';
proc glm;
        class temp;
        model ttlheat peakW avgW DMlst VDMlst kJDMlst JintlVDM time = temp ;
        means temp / lsd duncan;
        lsmeans temp / stderr pdiff;
run;
```

vii) Statisical Analysis: Comparison of measured and predicted values for R8

```
options linesize=96 pagesize=70 formdlim='-';
data test;
        input temp obs oxy cd amm vent cond condper finstein franke @@;
        cards;
        20 1 69 26 .9 1455 435 43 963 925
        20 2 72 34 .88 1413 -309 18 1002 962
```

```
        5 1 112 80 .69 1991 653 49 1574 1511
        5 2 116 67 1.01 2235 174 8 1618 1552
        -5 1 85 35 .89 1680 -164 9 1187 1139
        -5 2 119 79 .82 2026 -628 24 1660 1593
proc print;
        title 'Measured gases and heats';
        title2 'Run 8';
proc glm;
        class temp;
        model oxy cd amm vent cond condper finstein franke = temp ;
        means temp / lsd duncan;
        means temp / lsd duncan alpha = 0.10;
        lsmeans temp / stderr pdiff;
run;
```

viii) Statistical analysis: Comparison of the mean rates of heat produced during peak temperatures in R8

```
options linesize=96 pagesize=70 formdlim='-';
filename watts
DDE'Excel|D:\JURGEN\MASTERS\PHASEII\DATA\[MASS678.XLS]heat_time!R5C1
1:R22C13';
data test;
        infile watts ;
        input temp vessel watts;
        cards;
proc print;
        title1'2-way completely randomized design';
        title2'Watts produced at time 20';
proc glm;
        class temp;
        model watts = temp vessel(temp);
        test h=temp e=vessel(temp);
        means temp / lsd duncan;
        lsmeans temp / stderr pdiff;
run;
```