MODELLING THE TEMPERATURE OF A COMPOST MICROREACTOR IN ISOLATION

by

Mitchell Hawse

B.Sc., University of Northern British Columbia, 2016

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
PHYSICS

UNIVERSITY OF NORTHERN BRITISH COLUMBIA

April 2020

Title of Project/Thesis/Dissertation: ____________________

MODELLING THE TEMPERATURE OF A COMPOST MICROREACTOR IN ISOLATION

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Author ___ Mitchell Hawse ___

____________________ ________ April ________

Printed Name   Signature   Date 2020

Abstract

A mixture of waste-wood biomass and municipal biosolids waste was composted in a plastic container inside of an insulated chamber. The mixture of biomass and biosolids was approximately 50:50 and weighed 82.6 kg. The peak temperature of the compost was 32.4°C. The small scale of the compost system allowed the lower limit of the compost decomposition rate to be studied. A model was successfully developed to predict the core temperature of the compost using the ambient temperature in the insulated chamber. A literature review was conducted to determine literature values for the overall convective and conductive heat transfer coefficient, the dry mass fraction, and heat of combustion for both biomass and biosolids. The model used an optimization algorithm to calculate the rate constant for the experimental setup. The calculated decomposition rate constant was 0.0525 Day^{-1}.

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LIST OF DEFINITIONS

The following definitions are provided to build a language with which to discuss the research and are defined by the author.

Municipal Biosolids or **Biosolids** – Organic matter obtained after human waste has been treated at a waste water treatment facility.

Biomass – Shredded organic plant matter, usually from trees.

Compost – Any mixture of biological material that is decomposing by aerobic processes.

Dry Matter – The part of a material that can be broken down by biological or chemical processes, measured in kilograms of dry matter per kilogram of original substance.

Acknowledgements

I would like to acknowledge the following parties for their help and support during the preparation of this thesis. The list of people I could thank is a long one, but here I have chosen to mention a few of the most notable. First, to my supervisors, Dr. Ian Hartley and Dr. Mark Shegelski, as well as the rest of my supervisory committee: thank you for your guidance, insight, and ultimately your time. You gave me the skills and training that it takes to succeed while allowing me the freedom to choose my own way. The impact of your contributions to this work, as well as to my personal improvement, is something I will always value, thank-you. To Dr. Matthew Reid, thank-you for answering question I had about programming in Matlab, many hours of time spent debugging were prevented thanks to your knowledge and experience with it. To Conan Veitch, thank-you for countless conversations that included good distractions, excellent advice, and good old fashion pep talks. I would still be using Microsoft Word if not for you. To Gordon Everett for making the entire project possible by coordinating with Silvis and allowing me to obtain the biosolid material required to do my experiments, thank-you. To Gavin Schlamp for helping with the "dirty work", no amount of beer is worth loaning out your truck and assisting someone to load biosolids into it...twice...yet you did it for a 24 pack, thank-you. To my parents and family: your pride in, and support of, my journey through university from my very first day until now, have allowed me to stay the course, my sincerest appreciation and thanks. Finally, to my wife Emily, and my children Ramona, and George: you are my biggest distractions and my greatest support. The strength to see this through has all come from you, you are everything to me, thank-you.

Chapter 1

Introduction and Background

1.1 Introduction

Composting has been used to dispose of organic waste for millennia and its usefulness as an agricultural aide is well known [1]. It is also known that composting organic matter produces a significant amount of heat. Several studies have been done wherein composting is used as an energy source [2] [3] [4]. By attempting to use composting as an energy generating method for waste disposal, two issues arise: (1) the temperature of the compost can rise too high causing the compost to self-ignite [5]; and (2) the compost can become poorly aerated and, consequentially, be quite odorous [6]. To take advantage of the energy released by compost while minimizing the occurrence of these two issues, it is important to understand how the physical properties of compost relate to the rate of decomposition and heat generation. Mathematical models have been developed to predict the temperature of compost and its dependence on physical parameters such as composition, moisture content, and dry matter content. Studies have also determined values for the characteristics of compost systems such as the energy released per kilogram, the degradation rate, and the fraction of dry matter for different compost materials.

Most of the studies done are either conducted on large-scale outdoor compost piles or specialized sealed indoor compost reactors, both of which are not relevant for small composting projects. One of the objectives of this work was to characterize smaller scale compost systems. The following sections present a broad overview of composting theory followed by a model for predicting the temperature of municipal biosolid waste being composted in an isolated microreactor.

1.2 Background

1.2.1 Overview

In this section, relevant experimental research works, as well as mathematical modeling approaches, are identified. The research cited introduces the type of research being done with compost, the rationale for doing it, and the systems constructed to do the research. The questions that these studies answer, as well as ones they do not, will be discussed. The key contributions made by these studies that were relevant to this work have been highlighted throughout.

1.2.2 Background

As indicated earlier, composition, moisture content, and dry matter content are parameters to consider when studying energy generation of a compost. Further to these, air circulation, as well as microorganism type play a roll in energy generation. These are discussed in detail below.

A numerical model was used to predict the thermodynamics, kinetics, and energy use of composting systems [2]. The focus was not on extracting energy from compost, but on how to obtain the highest quality compost for agricultural purposes, namely as a soil amendment. Compost intended for agriculture use needs to be pasteurized, should be a homogeneous mixture, and should have a low internal temperature gradient while composting. These factors would be of concern for a compost project designed for energy extraction as well since once the composting has completed the remains will be of higher value if they meet these criteria.

Based on these criteria, higher quality compost was obtained when the temperature of the compost bed was regulated and kept consistent throughout the pile [2]. This was achieved by recycling some of the air that had already been blown through the sealed compost container back through it again. However, there were a couple of drawbacks to the air recirculation process used: (1) it took a substantial amount of energy to power the air recirculation system; and (2) after recirculating the air several times the air was sufficiently warmed such that it was no longer able to remove heat from the pile. When this happened, the overall temperature of the process increased, and the rate slowed.

The experimental apparatus built for this work was designed to only supply minimal ambient air to the compost system without re-circulation. This was done to maintain aerobic conditions in the compost without warming it.

In another study the cost associated with setting up and running a compost heating system compared to leading competitors, namely geothermal and solar power, was studied [4]. Compost heat was more expensive for water heating than solar, and slightly more expensive for spatial heating than geothermal. However, results showed that compost provided the most "reliable" heat when compared with solar and geothermal for both spatial and water heating. The criteria for reliability was that compost heat could be used for a larger portion of the year compared to solar and geothermal [4]. The results for reliability were climate dependent and further work needed be done to completely characterize how ambient temperature affects the compost temperature. It was noted that because of differences in seasonal temperatures, compost heat would only be able to be used approximately 91% of the time for spatial heating and 70% of the time for hot water supply. For this reason, a boiler was required for backup spatial and water heating. Based on these findings it would be desirable to be able to predict how ambient temperature affects the compost temperature.

The effects of the presence of different types and amounts of bacteria on the temperature of compost was studied [3]. The temperature of the compost was measured at various stages. This data was then compared with a model for predicting compost temperature. The model took many variables into account including oxygen content, moisture content, porosity of the compost, and density of the compost. From this study it is clear that understanding how the degradation rate of compost varies over time with respect to variation in the bacteria population is necessary for predicting the temperature of the compost.

Given the above discussion, the key topics to consider in this work were: (1) how the ambient temperature and size of the reactor affect the temperature of compost, and (2) how the composition of the compost, as well as bacteria population type, affect the degradation rate. Below are models that were developed to predict the temperature of compost. Aspects of these models were used when developing the model in this work.

1.2.3 Modelling

Testing of the thermal properties of compost made from municipal waste was investigated to quantify the heat energy released by composting biosolids [7]. The municipal waste was classified as sorted "domestic waste". The method used to compost the biosolids was an insulated chamber along with a compressor to push air through the compost pile. The pile was insulated in order to help determine the heat released during the composting process. Two different quantities were measured to allow the amount of energy released to be calculated: (1) the total calorific loss that occurred during composting, and (2) the amount of organic carbon loss throughout the process. The study established a numerical value for the energy released per kilogram of municipal waste composted of 900 kJ kg^{-1}, but noted that the energy released per kilogram of compost varies substantially depending on the material used. It was noted that follow up research needed to be done to characterize how cooling the municipal waste would affect the composting process and how efficient extracting the heat would be. This work demonstrated that composting could be used to extract energy from waste, and that the amount of energy available depended on the composition of the compost.

In order to model the temperature of compost made from municipal biosolids it was necessary to know the energy available in municipal biosolids.

A study quantifying the particulate emissions from the combustion of municipal biosolids determined the heat of combustion for biosolids [8]. The biosolids went through a treatment process involving de-watering and pulverization before being co-fired with coal. Knowing both the heat of combustion for the coal, as well as the energy output from the combustion, the heat of combustion for the biosolids was determined. It's value was approximately 6.6 MJ kg^{-1}.

Prediction of the temperature in a compost pile based on energy flow was done on an industrial scale [9]. The model developed used mass transfer and solar exposure as sources of energy flow into the system, and considered conductive, convective, evaporative, and radiative losses as sources of energy flow out of the system. The model was used to predict the temperature of the compost over a fifty-day period while considering how varying the airflow rate affected the temperature of the pile. It was shown that increasing the airflow rate reduced the temperature of the compost. It is important to note that only loss terms depended on the airflow rate, and the decomposition rate was assumed to be constant, so there was no mechanism for the temperature to increase with airflow. The rate constant used was assumed to be the maximum value from published literature [10]. This model therefore represents a compost system under optimal conditions with oxygen levels maintained at or above those required by the bacteria.

The physical parameters used in a model that optimized the efficiency of the composting process were estimated [10]. The parameters studied were dry matter content, aeration, and ambient temperature. Their effects on the rate at which degradation of compost occurred was observed. The study showed that the decomposition rate K was a function of the oxygen consumption and stated that its value should be experimentally determined for the specific materials to be composted. The study then experimentally determined the reaction rate for a compost mixture made from chicken droppings and gave a theoretical value ($K = 0.048$ Day^{-1}) for this setup [10].

1.3 Compost Theory

To understand the heating of compost, a discussion about the underlying mechanism is required. A description of the processes that occur during composting and how they affect the temperature of the compost is presented below. This information was considered when the model in this work was developed.

In a compost system that is isolated[1] from the environment, and where the temperature does not go high enough for oxidization of cellulosic materials to occur [5], the only source of thermal energy is biological decomposition [9]. The flora of microorganisms that provide decomposition is complex, as are the specific metabolic processes used, but bacteria account for the majority of the decomposition (87% *genus bacillus* [11]). For the purpose of this work, it was assumed that the heating due to microorganisms was caused by only bacteria, and that there was no

[1] A system is isolated by having it insulated to minimize the effect of environmental temperature changes

oxidation.

The rate of decomposition of compost would be impacted by this assumption. Different types of microorganisms break down the various components of compost (sugars, starches), and these processes occur at different rates [6] [7]. The overall decomposition rate would be a function of these individual rates. The purpose of this work was not to characterize the relative microorganism populations in compost and doing so was beyond its scope.

In the model presented, a "best fit" rate constant was calculated for simplicity. A discussion of how the model could be adapted to include more than one type of decomposition is included in Chapter 4.

The general heating mechanism induced by bacteria is simple. Organic matter along with oxygen is consumed and broken down into smaller substituents. Through this process energy is released and the mass of the compost is decreased. The energy released heats the compost. There are two main phases to the heating of compost: (1) the mesophilic phase, and (2) the thermophilic phase. The mesophilic phase is the first phase of compost decomposition and is characterized by lower temperatures and the bacteria that thrive in them (mesophilic bacteria). The temperature range of the mesophilic phase is from 10°C to 40°C [3]. The thermophilic phase is the second phase of composting where thermophilic bacteria are responsible for the decomposition. The temperature ranges from 40°C to 70°C during this phase. For municipal biosolids most of the decomposition happens during the mesophilic phase [12], this justifies the assumption that no heating due to oxidation occurred during the experiment conducted for this work.

Chapter 2

Model Theory

2.1 Theory

To characterize the compost heating for an isolated system, a mathematical model was developed based on other accepted models, as described previously [7] [9] [10]. The primary work used was [9], which modelled the temperature of the compost using

$$mc_p \frac{dT}{dt} = Q_{gain} - Q_{loss} = Q_{net} \tag{2.1}$$

where Q_{gain} and Q_{loss} were terms quantifying energy flow in and out of the compost (kJ Day^{-1}).

The model assumed a mass transfer mechanism for the energy generated by the compost mixture given by:

$$Q_{decomp} = H_c \frac{dm}{dt} \tag{2.2}$$

where H_c is the heat of combustion of 1 kg of compost [10]. The mass transfer equation was given by:

$$\frac{dm}{dt} = -K(m - m_e) \tag{2.3}$$

where m is the dry mass (kg) of compost, K is the degradation rate of the compost (Day^{-1}) which is typically measured experimentally, and m_e is the equilibrium mass of the compost; defined to be the mass of compost that remains after a substantial amount of time having been composted (6mo-1yr.).

To solve Equation 2.3, hold K constant, separate variables, and integrate to yield;

$$\ln\left(\frac{m(t') - m_e}{m_i - m_e}\right) = -Kt'. \tag{2.4}$$

Solving for *m(t')*, and combining with Equations 2.3 and 2.2 gives

$$Q_{decomp} = -H_c K(m_i - m_e)e^{-Kt} \tag{2.5}$$

where m_i is the initial dry mass of the compost. The negative sign before H_c indicates that energy was released by the mass transfer. This energy that is released by the mass transfer goes into the compost, and therefore

$$Q_{gen} = -Q_{decomp}. \tag{2.6}$$

where Q_{gen} is the energy flow into the compost do the decomposition. In the model, all of the energy flow terms were positive and the sign in front of the term was used to show that it either added to, or subtracted from, the net energy going into the compost.

Since the experimental design incorporated an insulated chamber, Q_{gen} was the only term that contributed to an increase in the net energy, whereas in other models there were terms accounting for heating of the compost by the sun. Therefore,

$$Q_{gain} = Q_{gen} \tag{2.7}$$

and all that remained to fully characterize Equation 2.1 was to determine the form of Q_{loss}.

In previous works Q_{loss} involved losses from different sources, including, evaporative, convective, conductive, and radiative [9]. Since this study was conducted in an insulated chamber, a simplified approach was taken. Typically, in other experimental setups, evaporation was the largest contributor to energy loss in compost at 70% followed by convective loss (20%) and then radiative loss (10%) [13]. The evaporative loss was large because of the high temperature achieved during composting. In the case of [9], a peak temperature of 71°C was observed. In this study the peak temperature was 32.5°C. Since evaporative loss scaled as e^{T}, the evaporative losses in the setup studied herein were much less than typical [14].

Radiative losses were considered to be negligible since they occur at the edge of the compost, and the temperature modelled in this work was that of the core. It is common practice to assume that conductive and convective losses dominate when considering the heat loss from the core of a compost pile to the surface [9].

As a result of these simplifications, Q_{loss} had the form;

$$Q_{loss} = Q_{con} = UA(T_c - T_{surf}) \tag{2.8}$$

where U was the overall convective and conductive heat transfer coefficient, A was the surface area of the compost vessel, T_c was the temperature at the centre of the compost, and T_{surf} was the temperature of the outer edge of the compost just inside the compost vessel (see figure 3.1) [15].

Since T_{surf} was not measured experimentally an important assumption in the model was that

$$T_{surf} \approx T_{amb}, \tag{2.9}$$

where T_{amb} was the ambient temperature of the room. This was a reasonable assumption because the thickness of the container was small compared to the distance from the centre of the compost, where the temperature probe was, to the edge of the compost. A more rigorous argument and calculation can be found in Appendix A.

Combining Equations 2.5, 2.6, 2.7, and 2.8 with Equation 2.1 gave;

$$Q_{net,n-1} = H_c K(m - m_e)e^{-Kt} - UA(T_{c,n} - T_{amb,n-1}). \tag{2.10}$$

Q_{net} needed to be calculated for each day that the temperature was to be modelled for. The index n was added in Equation 2.10 to represent the nth day. To compare the model to experimental data, the temperature for the nth day was calculated using:

$$T_{c,n} = T_{c,n-1} + \Delta T_{c,n-1} \tag{2.11}$$

where,

$$\Delta T_{c,n-1} = \frac{Q_{net,n-1}}{mc_p}\Delta t. \tag{2.12}$$

Equation 2.12, and Equation 2.11 were combined to give:

$$T_{c,n} = T_{c,n-1} + \frac{Q_{net,n-1}}{mc_p}\Delta t, \tag{2.13}$$

and along with Equation 2.10 were solved through an iterative process in MATLAB®. This process was performed as outlined below.

2.1.1 Numerical Algorithm

The following iterative process was used to calculate the temperature for each of the first 9 days after composting began. In order to calculate $T_{c,n}$ (Equation 2.13) both $T_{c,n-1}$ and $Q_{net,n-1}$ were required. The subtlety was in calculating $Q_{net,n-1}$. $Q_{net,n-1}$ depends on $T_{c,n}$; the quantity that was sought. This was a result of conductive losses scaling with the temperature of the compost pile. The more the temperature increased on day *n-1* ($\Delta T_{c,n-1}$) the more the conductive loss would have been during the same day (see Equation 2.8). The net difference between these two effects determined the change in temperature on day *n-1* ($\Delta T_{c,n-1}$), and thereby the temperature the next day ($T_{c,n}$).

This issue was solved by choosing an initial temperature for $T_{c,n}$ in Equation 2.10 that was lower than the anticipated final value of $T_{c,n}$ to be calculated using Equation 2.12. $Q_{net,n-1}$ was then calculated using the chosen initial value for $T_{c,n}$ and the result was used to calculate $T_{c,n}$ (Equation 2.13). The value obtained for $T_{c,n}$ (Equation 2.13) was inevitably larger than the initially chosen value used in Equation 2.10. If the difference was larger than 0.1°C the $T_{c,n}$ value used in Equation 2.10 was increased by 0.1°C and $T_{c,n}$ (Equation 2.13) was re-calculated. This process was repeated until both of the $T_{c,n}$ values were within 0.1°C.

Once the iterative process was done, the final $T_{c,n}$ was calculated. This process was repeated for all 9 temperature predictions (n = 1 - 9). Note: $T_{c,o}$ was the measured temperature of the compost at the outset of data collection.

2.2 Bounding Q_{loss}

In the model presented it was assumed that the only source of energy heating the compost and its environment was Q_{gen}. It was for this reason that the experiment was conducted in an insulated room. A consequence of insulating the system was that most of the energy released by the compost (Q_{loss}) would be retained in the room and increase the ambient temperature of the room. However, the insulated room was not a perfect calorimeter. The floor of the room was made of concrete which would have acted like a heat sink, removing some of Q_{loss} from the system. By determining the net energy flow into the room the expected increase in ambient temperature could be calculated. This provided a method to bound Q_{loss} and ensure that the model was not over or under accounting for the energy lost from the compost.

An estimate of the energy flowing out of the room (Q_{out}) through the floor was calculated (see Appendix A). The rate was determined to be:

$$Q_{out} = 39.2W. \tag{2.14}$$

On average, energy left the compost at a rate of:

$$Q_{loss} = 46.3W. \tag{2.15}$$

This resulted in a net energy flow into the room of:

$$Q_{net} = Q_{loss} - Q_{out} = 7.1W, \tag{2.16}$$

the equivalent of 613 kJ heating the air over the course of a day. The expected change in ambient temperature due to this energy released by the compost would be given by

$$\Delta T_{amb} = \frac{Q_{net}}{m' c'_p} \Delta t. \tag{2.17}$$

The terms m' and c'_p are, respectively, weighted mass and specific heat terms that take into account the different materials that were heated by the energy leaving the compost. Materials that needed to be included were the air in the room, the walls of the compost container, and the concrete floor. Including those materials in Equation 2.17 resulted in:

$$\Delta T_{amb} = \frac{Q_{net}}{V_{air}\rho_{air}c_{p,air} + \rho_{con}d_{con}A + m_{plastic}c_{p,plastic}}\Delta t. \tag{2.18}$$

Using the values from the Table 2.1 in Equation 2.18 gives.

$$\Delta T_{amb} = 2.1°C. \tag{2.19}$$

During the experiment the ambient temperature increased from 13.6°C to 17.5°C, an average increase of approximately 0.5°C per day. Although the expected temperature change was higher than the measured temperature change it should be noted that the choice for the thickness of concrete that was assumed to be heated was only 1 cm. This value was chosen somewhat arbitrarily. In reality much more of the concrete would likely have been heated as Q_{out} flowed through it. The fact that the temperature changes were on the same order verifies that the assumptions made in the model relating to how energy leaves the system, were valid.

Physical Values			
Parameter	Value [16]	Parameter	Value
$c_{p,air}$	1 kJ kg^{-1} K^{-1}	A	10 m^2
$c_{p,con}$	0.75 kJ kg^{-1} K^{-1}	d_{con}	0.01 m
$c_{p,plastic}$	2.25 kJ kg^{-1} K^{-1}	$m_{plastic}$	10 kg
ρ_{air}	1.225 kg m^{-3}	V_{air}	25 m^3
ρ_{con}	2400 kg m^{-3}		

Table 2.1: Physical Parameters for Calculating ΔT_{amb}

Chapter 3

Experimental Methods

This chapter is a description of the experimental systems and methods used to obtain the data for this work. The first section describes the components of the experimental setup. Then the methodology used to collect the data with the experimental apparatus is explained.

3.1 Experimental Setup

Compost container:

A high-density polyethylene container was used to hold the compost mixture. The top of the container was cut-off and therefore open to the air. The container was 87 cm tall, had a diameter of 59 cm, and a wall thickness of 2.2 mm.

Heat exchange system:

The heat exchange system consisted of a 25 m, 0.64 cm diameter copper pipe, a volume flow meter, and a garden hose. The garden hose was connected to a standard water line faucet on the one end and a volume flow meter on the other. The copper pipe was attached to the downstream side of the volume flow meter. The copper pipe was bent into a coil the width of the barrel (4 loops) and placed inside

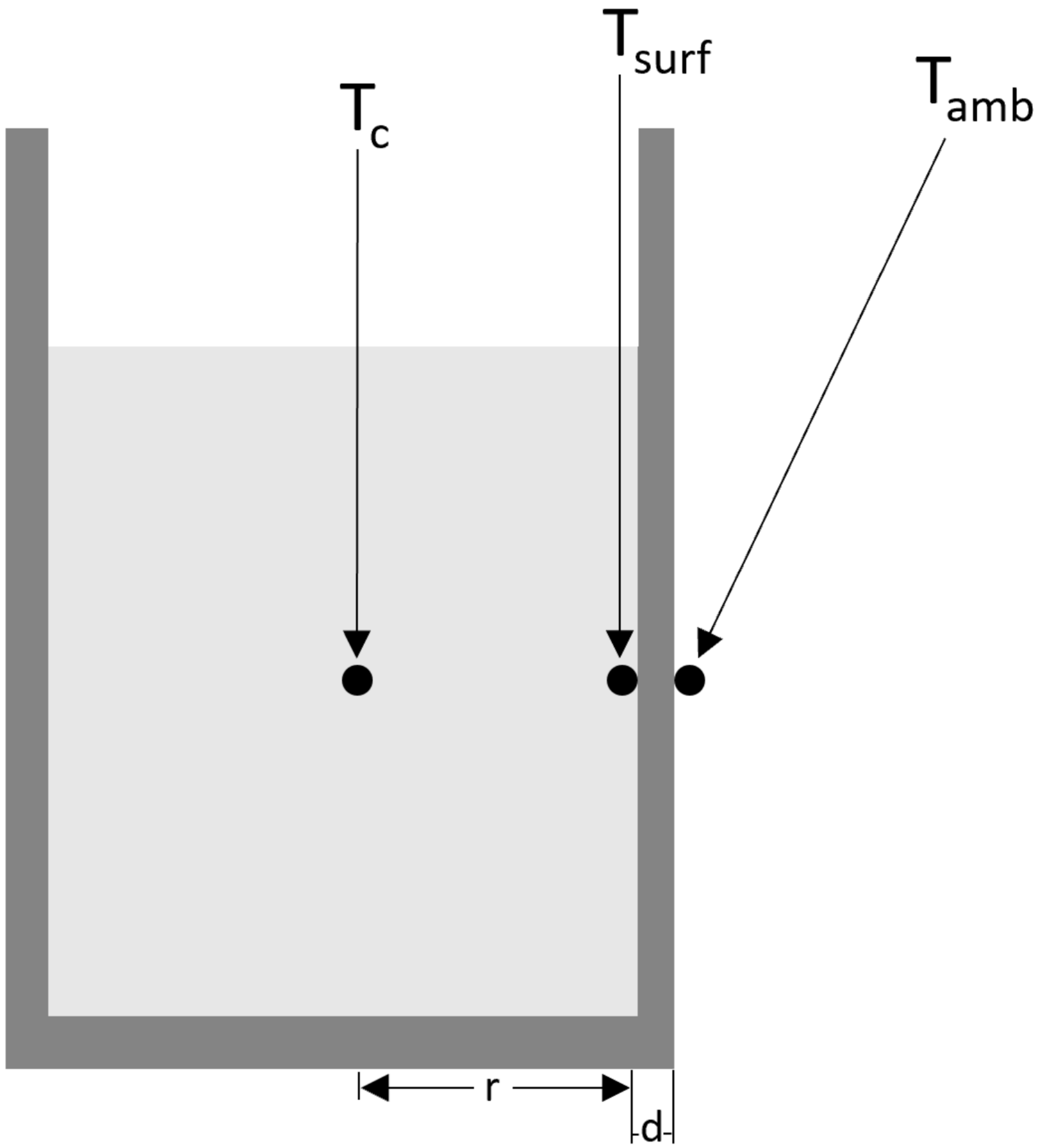

Figure 3.1: Diagram of experimental compost container showing thermocouple locations

the container. Note: the heat exchange system was not running while data was collected for this work.

Air Supply:

The experimental design of the oxygen supply system consisted of an air compressor, air hose, a piece of steel pipe, an air gun, and a Wi-Fi controlled timer power outlet. The air compressor was connected to the Wi-Fi timer power outlet which was plugged into a regular (110 V, 15 A) outlet. This Wi-Fi timer power outlet was used to set how long the compressor would run. The air compressor had a hose attached to it and the air gun was attached to the other end of the hose to discharge the air from the compressor. The air gun was connected to the pipe which was inserted into the compost mixture. The air gun had a trigger which was taped in the fully depressed configuration so that when the compressor turned on air immediately started going through the pipe into the compost.

Compost:

The compost mixture was made by mixing biomass and biosolids 1:1 by volume. One shovel full of biomass was placed in the barrel and then one shovel full of biosolids was placed inside the barrel. This process was repeated until the barrel was a third full. At that point a layer of dry grass clippings and leaves was added. This entire process was repeated twice more. This produced 3 combined layers of composite+clippings+leaves in the container.

Data Loggers:

The temperatures were measured using SmartReader 6 data loggers. Two thermocouples were used, each capable of taking three different measurements simultaneously. The thermocouples were used in tandem, each as redundancy for the other. The three temperature locations (see Fig 3.1) were on the copper coil (not shown) just downstream of the volumetric flow meter, in the centre of the compost pile a third of the way down, and on the copper coil immediately after if came out of the compost pile. T_{surf} in Fig 3.1 was not measured.

A secondary temperature probe was used to access the accuracy of the temperature reading of the thermocouple in the centre of the pile. This was done because the accuracy of the true temperature readings of the thermocouples was in question [17] (See Section 3.4 for a more in-depth discussion about the temperature measurement error). The secondary probe was a Rain Bird temperature probe. This temperature probe was checked periodically and compared with the reading from the thermocouple in the centre of the compost. It was found the actual temperature as per the Rain Bird temperature probe was on average about 3°C higher than the temperature measured by the thermocouples.

The System:

The whole apparatus was kept inside a large insulated commercial freezer. The approximate dimensions were 2.5 m x 4 m x 2.5 m. The freezer was not running for the duration of the experiment.

3.2 Data Collection

After the experiment was set up as described above the data-loggers were started, taking one measurement every minute. At the same time, the air supply system was set to supply air to the system for one minute every hour. The system was left to run for 24 hours at a time, once a day the door to the insulated room was opened, the secondary temperature probe was checked, and the data loggers were backed up. This process was repeated from July 22nd until July 31st.

3.3 Model Parameter Values

Values for all parameters besides the rate constant were taken from the literature or calculated using literature values. This was done so that the rate constant (K) could be calculated by fitting the model to the data. Having all other parameters fixed strengthened the model. Extensive research was done in order to determine physically realistic values that accurately reflected the physical setup used to collect the data in this work. Following are descriptions of the processes applied to determine the parameter values used.

Mass Ratio of Biosolids and Biomass

The compost mixture was made using equal volumes of biosolids and biomass. Determination of parameters such as, the specific heat, dry matter content (β), and heat of combustion required knowing the individual masses of biosolids and biomass. To obtain the respective masses from the total mass of compost, the density of one substance was required. Using the average literature density of biomass (ρ_{BM} = 336 kg m^{-3} (288-384 kg m^{-3}) [18]) the mass of the biomass was determined by:

$$m_{BM} = \rho_{BM}\frac{V}{2}. \tag{3.1}$$

where V was the volume of the compost container. The mass of the biosolids was calculated by:

$$m_{MBS} = m_{TOT} - \rho_{BM}\frac{V}{2} \tag{3.2}$$

Equilibrium Mass and β

The equilibrium mass of a material is defined as the mass remaining after a long period of time spent composting (on the order of a year). This mass does not break down with further composting [10]. β is the ratio of this equilibrium mass (m_e)

and the initial mass of compost given by:

$$\beta = \frac{m_e}{m_o}. \tag{3.3}$$

The value of β depends on the material being composted. For biomass it is 0.36 [10] and for biosolids it is 0.865 [10]. Taking a weighted average of these values based on the relative masses of biosolids and biomass resulted in a value of β = 0.711.

Specific Heat Capacity of Compost

The specific heat of the compost was calculated using literature values for the heat capacity of biosolids (2.98 kJ kg^{-1} K^{-1} [19]) and waste wood (2.30 kJ kg^{-1} K^{-1} [20]) and then taking a weighted average based on the mass fractions for biosolids and biomass. The resulting heat capacity was 2.77 kJ kg^{-1} K^{-1}.

Heat of Combustion

The heat of combustion for biosolids varies substantially in the literature due to varying compositions of the biosolids [7]. The value used in this work was 6.6 MJ kg^{-1} because it was experimentally determined for municipal sewage sludge that had undergone a similar treatment process as the biosolids used in this work [8]. The value for the heat of combustion of wood is better known. The standard literature value of 21.0 MJ kg^{-1} was used [18]. The weighted average value used was 10.7 MJ kg^{-1}.

Convective and Conductive Heat Loss Coefficient The literature value for the thermal conductivity (k) coefficient ranged from 0.26 - 0.43 W/mK for compost [7].

The convective and conductive heat loss coefficient (*U*) is related to (*k*) by:

$$U = \frac{k_c}{r} \tag{3.4}$$

where *r* is the distance from the centre of the compost pile to the edge of the compost container [15]. The resulting range of values for (*U*) was 79-130 kJ m^{-2} K^{-1} Day^{-1}. The wide range in values is due in part to the dependence of the thermal conductivity on moisture content. The thermal conductivity of compost increases linearly with moisture content [21]. The moisture content of the compost used in this work was 60% and was just in the predicting range (20% - 65%) of the study cited.

Summary of Physical Parameter Values

Physical Values			
Parameter	Literature Values	Parameter	Experimental Values
β	0.711	K	0.0525 Day^{-1}
ρ_{BM}	336 kg m^{-3}	m_{BM}	25.2 kg
c_p	2.77 kJ $kg^{-1}K^{-1}$	m_{MBS}	57.4 kg
H_c	10.7 MJ	m_{TOT}	82.6 kg
U	130 kJ m^{-2} K^{-1} Day^{-1}	r	0.286 m
		V	0.15 m^3

Table 3.1: Physical Parameters for Modelling

3.4 Experimental Error

As in all experimental systems error was introduced during the data collection process. There were three dominant sources of error affecting the results: (1) The thermocouples that were used have a measurement error; (2) the system studied was not a perfectly isolated; and (3) the exact density of the biomass was unknown. These sources of error are discussed in more detail below.

Thermocouple error:

The thermocouples used have an associated error in measurement of:

$$T_{\text{Couple,Error}} = 4.05°\text{C}. \tag{3.5}$$

However, the thermistor built into the thermocouple system has an error of only:

$$T_{\text{Thermister,Error}} = 0.7°\text{C}. \tag{3.6}$$

The thermistor error bound the error in measurement of the temperature since relative temperature data was used in this study.

There were concerns that the thermocouples used might give erroneous results since they were old and may have been damaged from a previous study [17]. For this reason two different thermocouples were used in order to corroborate the results. A more in-depth description of the error associated with the thermocouples can be found elsewhere [17], p. 99.

The System:

The room that contained the compost, although well insulated, was not a perfect calorimeter. Loss of energy from the system due to conduction through the walls and concrete floor would have occurred. Additionally, the door to the chamber was opened approximately once every 24 hrs to backup the temperature measurements from dataloggers. This let some of the air inside the freezer escape and would have caused some unaccounted energy loss from the system. These losses would have contributed to the ambient temperature in the chamber not increasing as much as expected.

Biomass Density error:

The composition of the biomass was not homogeneous. The smallest pieces were comparable to sawdust and the largest were small branches. The species of tree that the biomass was composed of was also unknown (and possibly varied). This made the uncertainty in the value for the density of the biomass large and required an average literature value for the density of biomass to be used. The range in density was used to find an upper and lower bound for the model predictions. The high, average, and low values of biomass density were each used to calculate a different set of values of each parameter discussed in the preceding section. The modelling algorithm was then run with these three different sets of values. Results for the three runs were plotted in Fig 4.1.

Chapter 4

Results and Discussion

The results of this study are illustrated in Figure 4.1 and Figure 4.2. Figure 4.1 shows the temperature predicted by the model compared to the measured temperature, along with the ambient temperature, and the error in ambient, predicted, and measured temperatures. Figure 4.2 shows the residuals of the model predictions.

In this chapter the first two sections discuss the model predictions and residuals individually, this is followed by a section describing alternative modelling approaches that were considered. A section discussing the computer modelling methodology concludes the chapter.

4.1 Model Predictions

The results in Figure 4.1 show that the model agrees with the experimental data, within error, 9 out of 10 days. The temperature on Day 2 is outside the prediction of the model. The model used the experimental ambient temperature and literature values to predict the temperature of biomass and biosolids compost. Upon inspection of the ambient temperature it was observed that after Day 1 it increases monotonically. Given that the predicted temperature of the compost depended on the ambient temperature, it was intriguing that the predicted temperature has the same trend (oscillating up and down) as the experimental temperature after Day 6 despite the ambient temperature continuously increasing. This was an encouraging sign that the model used the correct form of loss terms. The loss terms become dominant later in experimental time as a result of the exponential in Q_{gen} becoming small as t increases.

The temperature on Day 2 being outside the model's predictive power was not unexpected. Two of the assumptions in the model contributed to this result: (1) the decomposition rate was assumed to be constant; and (2) only one type of bacterial decomposition was assumed to occur. The decomposition rate of the compost would vary with bacteria population which varies with time, but the model used an optimized average decomposition rate constant. The decomposition rate constant, as determined by fitting the model to the data, was influenced strongly by the lower temperatures that occur later in time. The composting conditions at this time were less optimal, and consequently the decomposition rate was lower than it would be when decomposition first started. Additionally, the decomposition rate depends on the substrate being consumed by the microorganisms. The easily digestible substances decompose earlier and a greater rate [7].

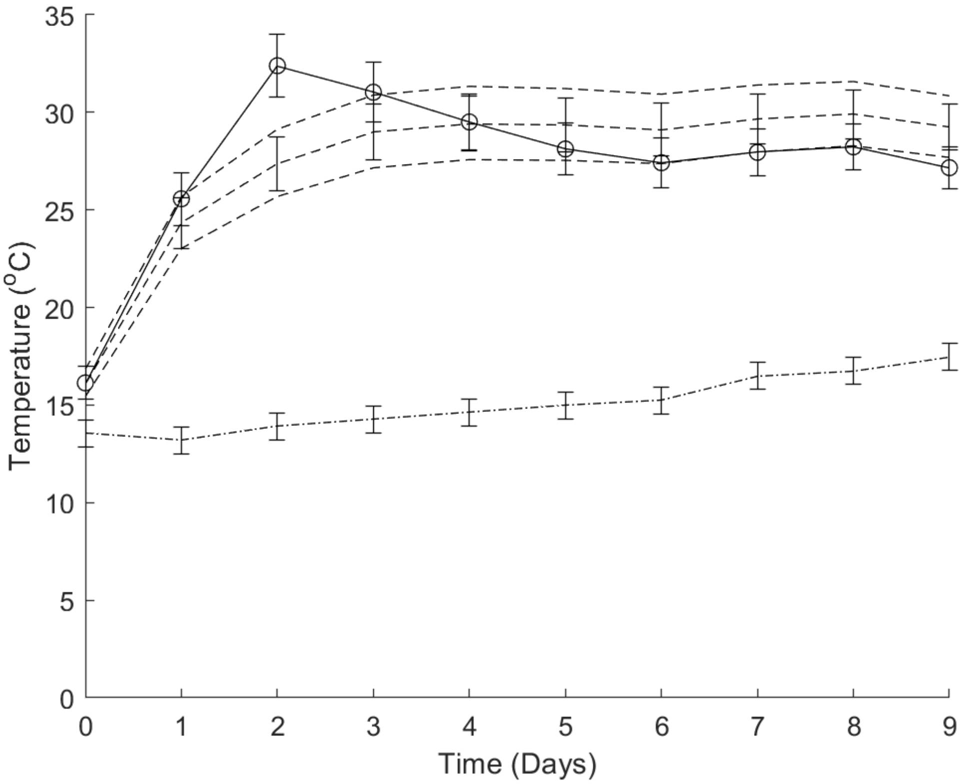

Figure 4.1: The measured temperature at the centre of the compost (-o-) along with error bars, the predicted temperature based on the model (- -) including error bars, the measured ambient temperature (.-) along with error bars

4.2 Residuals

Initially the residual plot in Figure 4.2 seems to present an issue; the distribution of the residuals appears heteroscedastic. However, upon further inspection this was not a concern. The sizes of the individual residuals (average of 1.86°C) are on the order of the error in measurement (average 1.6°C). A plot of the measurement errors added in quadrature alongside the residuals (Figure 4.2) shows that only two of the residuals are outside the error band, and of those two, only one is more than 0.5°C outside the error band. Conclusions cannot be drawn from residuals that are on the order of the error.

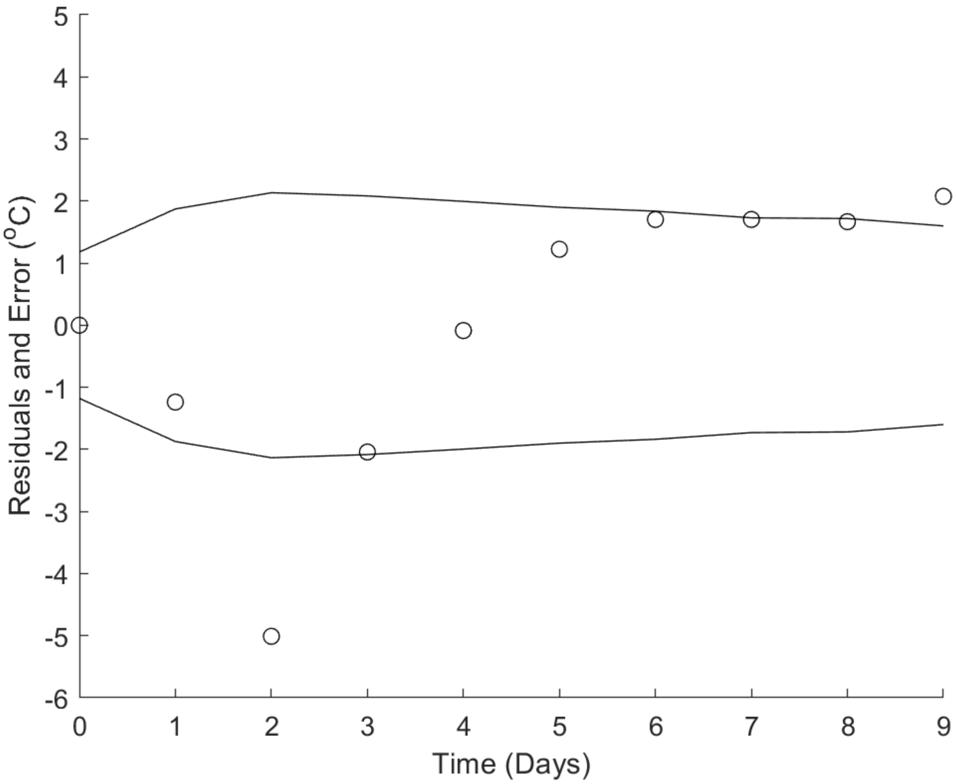

Figure 4.2: Residual values (o), measurement error (–)

4.3 Alternative Modelling Approaches

Considering the simplicity of the model, the fit to experimental data is quite good. This section characterizes how the different assumptions incorporated in the model affected the results. There were two primary assumptions that simplified the model substantially.

The first was that the decomposition rate was constant in time. This assumption was used for three reasons: (1) it simplified the computer algorithm, (2) it strengthened the model by reducing the number of free parameters, and (3) it is consistent with the assumption in [9].

The second assumption was that only one type of microorganism population contributes to the decomposition rate. Again, this assumption reduced the number of free parameters in the model, and simplified the computer algorithm. The following sections show how these assumption affected the model results.

4.3.1 Time Dependent Rate Constant, K

As discussed the decomposition rate was assumed to be constant for this work. Having a time-dependent rate constant is an intuitive next step and work was done to determine its form [10]. However, the time-dependent form of the decomposition rate determined was for composting in the temperature range 35-60°C. The experimental temperatures in this work were not in that range, and therefore unable to be modelled with the time-dependent decomposition rate developed. Determining a time-dependent rate constant for the appropriate temperature range was beyond the scope of this work. To understand the impact of a time-dependent decomposition rate without having to determine it's form an alternate approach was used.

Values for the decomposition rate at different points in time were chosen so that the model temperature was within 0.1°C of the experimental temperature. A plot of decomposition rate versus time was then generated (see Figure 4.3). From the figure it is clear that the form of K mirrors that of the experimental temperature. More explicitly, the model is sensitive to the decomposition rate. This was expected since: (1) K was the only parameter in the model; (2) the model was very simple; and (3) K is responsible for much of the physical character of the system.

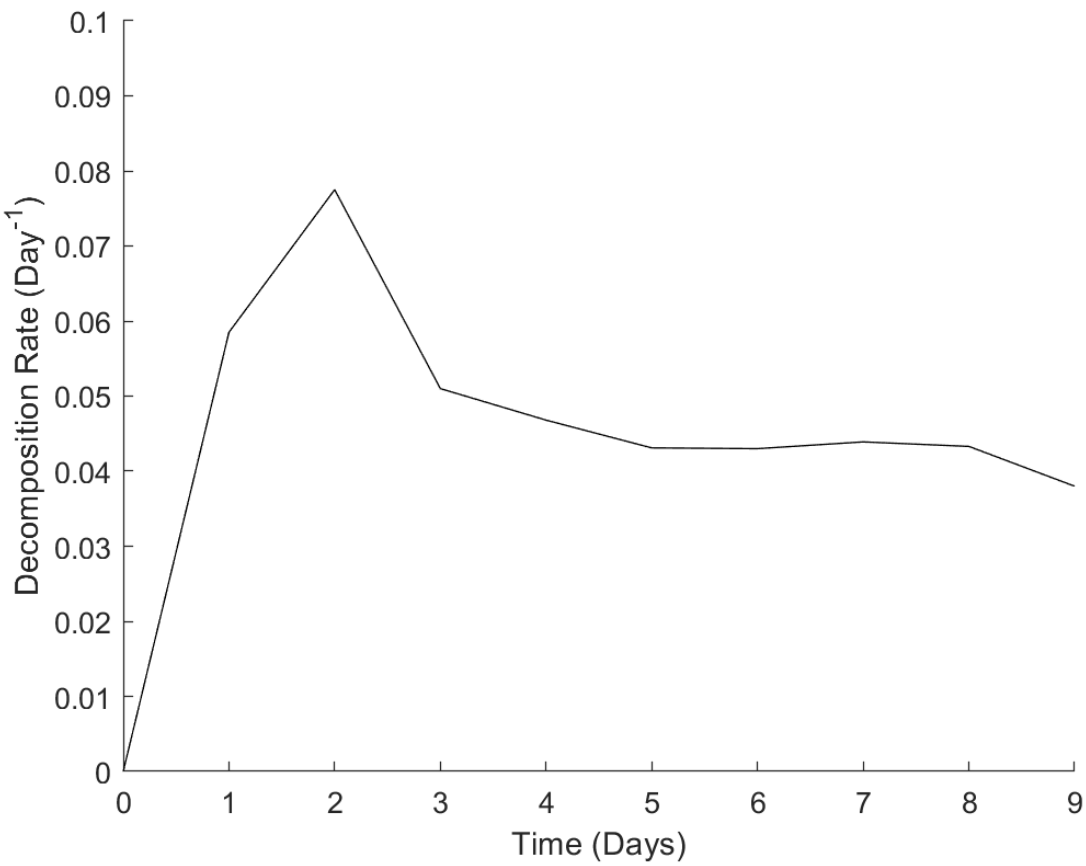

Figure 4.3: Time dependent decomposition rate obtained from fitting model to experimental data using handpicked values.

4.3.2 Two Bacteria Population Model

In Section 1.4 a discussion about how the microorganisms in compost cause it to heat up is given. A brief discussion of the types of microorganisms that contribute to the heating was presented. The argument was made that determining the individual components of a multi-microorganism population rate constant was beyond the scope of this work. This section presents an example of how including multiple microorganism populations impact the model results. It was modelled by having a second energy generation term of the form in Equation 2.5 with a different decomposition rate. The modified version of the model was then run through the same algorithm discussed in Chapter 2.

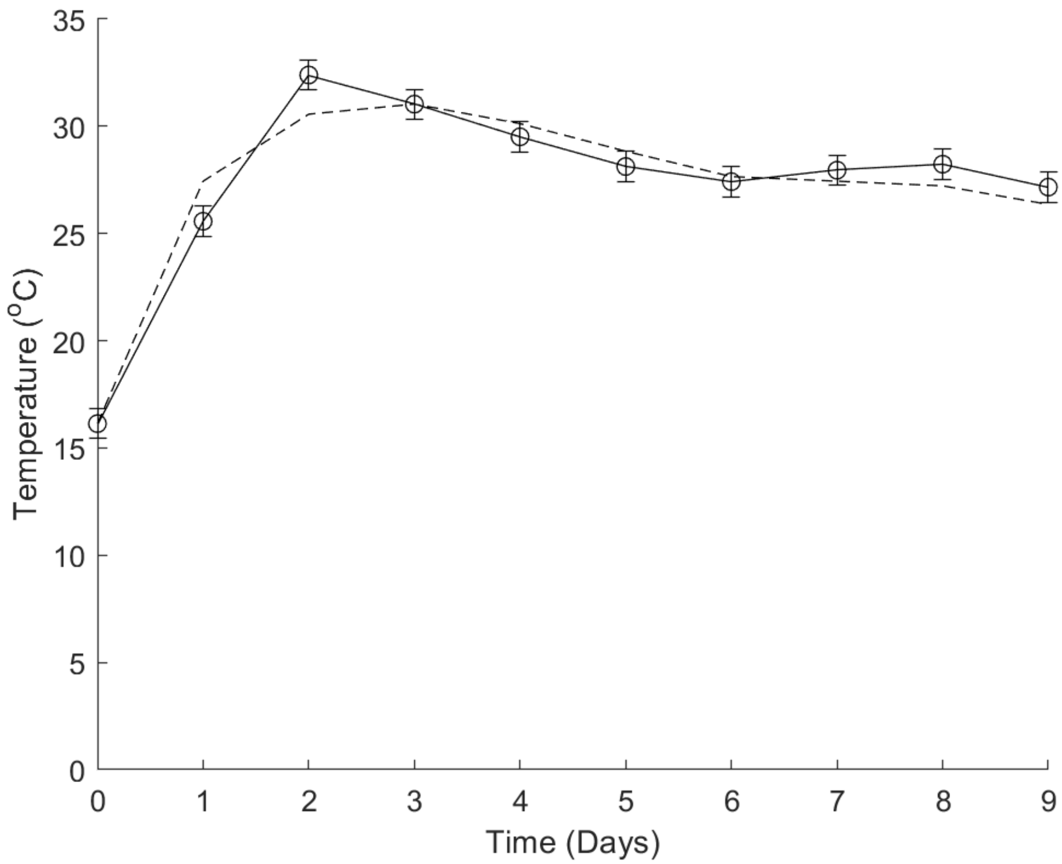

Figure 4.4: Two microorganism population fit (–) to experimental data (o) with error bars, k_1 = 0.0342, k_2 = 0.3147

Fig 4.4 shows the result of including another bacteria population. The peak temperature on day 2 is much closer to being in the range of the model. In general the predicted temperature was closer to the experimental temperature than for the original “one population” model presented in this work. It should be noted that this approach was not rigorous and was done for demonstration purposes. The implications of the results are therefore limited, but do serve to show the potential of a two population model were one to be developed.

4.4 Computer Modelling Methodology

Initially Microsoft Excel® was used to analyze the data and generate the model results. Excel® was chosen because the author was experienced with it and it allowed the author to very quickly reproduce an approximation of the model in [9]. Excel also had the advantage that the data and calculations could all be displayed visually. This allowed for easy debugging of the early versions of the model. These early versions of the models were very useful for interpreting model predictions and troubleshooting, but had limited success at reproducing the experimental results. Some of the assumptions used to simplify the model to the point it could be modelled in Excel were too restrictive. The models developed in Excel used average values for the daily temperature increases needed to calculate the amount of energy lost throughout that same day. A better approach was to use the iterative algorithm discussed in Section 2.1.1 to determine the predicted temperature each day and use this more accurate value to calculate the energy loss. An iterative process like the one employed could have been done using Excel but would have been much more difficult. This ultimately resulted in the author using MATLAB® for the remainder of the modelling done. The technique developed to approximate the convective and conductive losses in the model, using the iterative algorithm, is itself a useful result of this work. All results presented in this chapter were obtained using MATLAB®.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The model satisfactorily predicts the temperature of the compost for 90% of the data using only literature values for the materials composted and the ambient temperature in the isolated system. This was an objective identified in the introduction of this work. Additionally the decomposition rate constant for municipal biosolids and wood waste compost was determined. The value of the constant was $K = 0.0525$ Day^{-1}, and this value is consistent with the literature for compost made from similar materials including animal waste [6] [10].

The only data point that is not within the range of error values was Day 2, and the difference between the predicted and experimental temperature was large (2.7°C). This indicated that the model was missing a significant contribution to the energy into the system at this time. The mostly likely cause for this under-accounting of energy into the system was the assumption that the decomposition rate of the compost was constant.

5.2 Future work

Chapter 1 of this work pointed out several topics worth investigating and two of them were investigated herein. The first was the determination of the decomposition rate for biosmass and biosolids compost, and the second was the correlation between the ambient temperature and the temperature of the compost. In this section the topics that were not addressed in this work, but that are the logical next step are discussed.

Sections 4.3.1 and 4.3.2 briefly discuss the benefits of considering a time dependent decomposition rate, and a two bacteria population model respectively. Both of these topics are worth investigating further in the future.

A third topic that was highlighted in the introduction of this work, but not focused on after that, is the size of the compost pile. The temperature of the compost studied never went above 35°C. This is not typical, and often not desired. Higher temperatures are usually maintained in order to "pasteurize" the compost. However, in very niche settings, limiting the compost to lower temperatures could be of interest. Further work to characterize how the size (mass) of the compost pile affects the decomposition rate and the maximum obtainable temperature would be beneficial.

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Appendix A

Calculations

A.1 $\mathbf{T}_{surf} \approx \mathbf{T}_{amb}$

An important assumption in the model is that;

$$T_{surf} \approx T_{amb}. \tag{A.1}$$

The calculation verifying the validity of this assumption is a familiar heat transfer problem. First using;

$$Q = \frac{kA(T_1 - T_2)}{\Delta x} \tag{A.2}$$

where Q is the heat flow, k is the thermal conductivity of a material, A is the area though which the energy flows, and Δx is the distance the energy flows.

Referring to Figure A.1 and knowing that heat flow through the compost is the same as the heat flow through the compost vessel yields;

$$\frac{k_c(T_c - T_{surf})}{r} = \frac{k_p(T_{surf} - T_{amb})}{d} \tag{A.3}$$

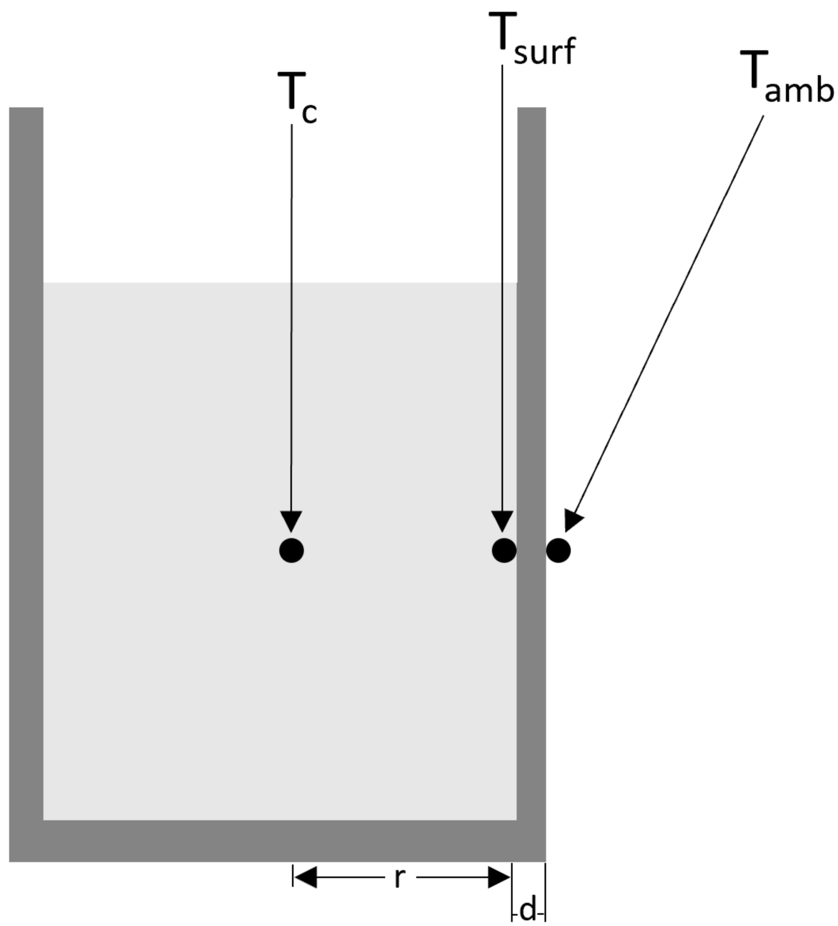

Figure A.1: Heat transfer diagram

or

$$T_{surf} = \frac{\frac{k_c d}{k_p r} T_c + T_{amb}}{1 + \frac{k_c d}{k_p r}} \tag{A.4}$$

using the values from Table A.1 yields;

$$\frac{k_c d}{k_p r} \approx 0.0066 \tag{A.5}$$

and therefore;

$$T_{surf} \approx T_{amb} + 0.0066 T_c. \tag{A.6}$$

Equation A.6 shows that even for a relatively large T_c the original approximation in Equation A.1 is good.

A.2 Q_{loss}

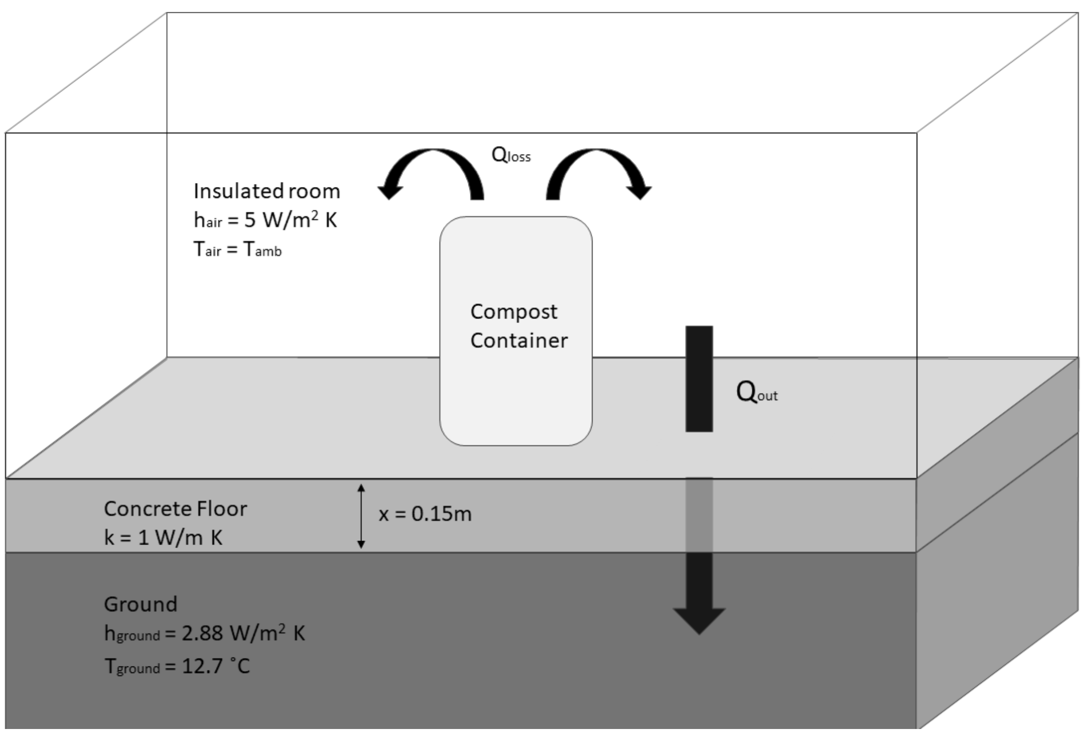

Figure A.2: Insulated room diagram

A rough calculation was done to bound the energy leaving the system through the concrete floor. The energy flow is give by:

$$Q_{out} = \frac{T_{inside} - T_{outside}}{R_{tot}} \tag{A.7}$$

where T_{inside} is T_{amb}, $T_{outside}$ is T_{ground}, and R_{tot} is the total thermal resistance between the two temperature locations. Here

$$R_{tot} = \frac{1}{h_{soil}A} + \frac{x}{k_{concrete}A} + \frac{1}{h_{air}A}. \tag{A.8}$$

combining these last two equations gives

$$Q_{out} = \frac{T_{amb} - T_{earth}}{\frac{1}{h_{soil}A} + \frac{x}{k_{concrete}A} + \frac{1}{h_{air}A}}. \tag{A.9}$$

using values from Fig A.2 [16] [20], Table 3.1 and the average value of T_{amb} (15.4°C) results in

$$Q_{out} = 39.2W \tag{A.10}$$

Summary of Physical Parameters

Physical Values			
Parameter	Literature Values	Parameter	Experimental Values
h_{air}	5 W m^{-2} K^{-1}	d	0.0022 m
h_{soil}	2.88 W m^{-2} K^{-1}	r	0.286 m
k_c	0.43 W m^{-1} K^{-1}	x	0.15 m
k_p	0.5 W m^{-1} K^{-1}		

Table A.1: Physical Parameters for Calculating Q_{loss}

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Candidate for the Degree: Master of Science in Physics

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The thesis as a number of typpographical/grammatical errors to be corrected, and reference completion to double check - the supervisor noted that these may be due to use of LATEX, and would revisit these with student.

All committee members are sending their typographical/grammatical corrections to supervisor, who will pass on to student.

Name of Chair of Examining Committee: Dr. Andrea Gorrell

Date: April 22, 2020

Signature: Andrea Gorrell

THESIS APPROVAL

Name: Mitchell Hawse

Degree: Master of Science in Physics

Title: MODELLING THE TEMPERATURE OF A COMPOST MICROREACTOR IN ISOLATION

Chair of Defence:

Dr. Andrea Gorrell
University of Northern British Columbia

Examining Committee:

Supervisor: Dr. Ian Hartley
University of Northern British Columbia

Co-Supervisor: Dr. Mark Shegelski
University of Northern British Columbia

Committee Member: Dr. Mark Reid
University of Northern British Columbia

Committee Member: Mr. Maik Gehloff MASc
University of Northern British Columbia

External Examiner: Dr. Ronald Thring
University of Northern British Columbia

Date Approved: April 22, 2020

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Cheers,
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Name: Mitchell Hawse

Degree: Master of Science in Physics

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Chair of Defence:

Andrea Gorrell

Dr. Andrea Gorrell
University of Northern British Columbia

Examining Committee:

Supervisor: Dr. Ian Hartley
University of Northern British Columbia

Co-Supervisor: Dr. Mark Shegelski
University of Northern British Columbia

Committee Member: Dr. Mark Reid
University of Northern British Columbia

Committee Member: Mr. Maik Gehloff MASc
University of Northern British Columbia

External Examiner: Dr. Ronald Thring
University of Northern British Columbia

Date Approved: April 22, 2020