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Optimizing Heat Extraction from Compost

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ABSTRACT Composting is an exothermic process from which useful energy can be captured in the form either of electricity or of heat for air or water. What the literature lacks are rigorously validated models of such systems and a systematic approach to their design. Previously published models represented changes in process variables (temperature, humidity, oxygen concentration, etc.) in the solid, liquid and gas phases of the compost. In this study, an updated model was created in the commercial, finite-element, multiphysics software COMSOL®, to simulate mass and energy balances in a cylindrical composter. The model will be validated against empirical data from barrel composters and will be used to develop guidelines for the optimal design of compost heat extraction systems.

Keywords: compost, energy, aerobic digestion, heat extraction, heat energy, renewable energy, waste

INTRODUCTION

In 1933, Browne observed that piles of hay spontaneously combusted as a result of microbial activity creating volatile hot pockets within the hay that then reacted with sudden influxes of oxygen in the form of external air (Browne, 1933). Since then it has become well known that microbial activity can raise the temperature of compost to temperatures as high as 65°C (Diaz, 2007). This high heat phase of composting is important to convert biological waste into the useful stable material that is compost. It can be used to reduce plant pathogens, improve the growth of agricultural crops and improve soil quality, as it contains many nutrients, such as nitrogen, phosphorus and trace metals.

Composting could have yet another purpose. Recent attempts have been made to extract useful heat from the microbial degradation of substrates in compost. This heat can be used to heat water to warm residential or agricultural facilities such as green houses (Antizar-Ladislao, Irvine, & Lamont, 2010; Raclavska, Juchelkova, Skrobankova, Wiltowski, & Campen, 2011). In these studies a heat exchanger was used to extract heat from compost at the thermophilic stage of the process. A possible drawback to this method is that extracting heat from compost might slow down or stall the process by removing the heat necessary to maintain microbial activity. However Viel et al. (1987) were able to prolong microbial activity by varying the time at which a heat exchanger was activated,; either before or after peak oxygen consumption had been reached. If the heat exchanger was activated after peak compost temperature had been reached oxygen consumption was prolonged. Starting the heat exchange before this point decreased oxygen consumption. They were able to prolong microbial activity although much of the heat produced was lost through heat dissipation.

An explanation for this may lie in the microbial profile of the composting mass. Certain microbial species cannot survive at temperatures above 40°C while others thrive at temperatures of 60-70°C. This means that from the mesophilic to the thermophilic composting stage there is a turn over in the kind of microbial biomass that exists within the compost (Diaz, 2007). It is possible that starting heat exchange early affects the mesophilic microbes that are more sensitive to temperature changes, something that may not be an issue with more resistant thermophilic microbes.

A study by Mustapha (2013) maintained that over half of Canadian households (61%) participated in some form of composting in 2011. This was reported to be a considerable increase compared to data collected in 1994. Quebec was reported to be one of the provinces with the largest increase in these percentages (up to 42% from 8 % in 1994). In addition, the city of Montreal has recently announced the construction of four large composting facilities to treat the city's increasing quantities of disposed organic waste and to comply with a provincial moratorium prohibiting the disposal of organic residues to landfill. This means that with such large quantities of organic waste processed in these facilities it is advantageous to further investigate the possibilities of compost as a heat source.

A number of studies have investigated the amount of heat energy that can be produced during composting. Before citing the results, it is important to note that it is hard to accurately predict such energy because the composition of organic waste is so varied. Haug (1993) reported that based on the heat of reaction calculations for the breakdown of organic compounds to carbon dioxide and water, it was possible to obtain 8.8 MJ/kg to 38.9 MJ/kg of dry organic matter. A later study gives a value 17.8 MJ/kg of dry organic matter (Themelis, 2005). However these values are theoretical and other experiments have shown that the cumulative amount of heat energy produced from the composting of wheat straw was 17.06 MJ/kg (Stainforth, 1979). In the case of poultry droppings 12.8 MJ/kg was measured (Sobel & Muck, 1983). It is important to note that these values are cumulative and are not directly useful for estimating the amount of useful heat that can be extracted, which is optimal during the thermophilic phase. Guljajew and Szapiro (1962) reported that 961 kJ/kg was generated during the high temperature phase. These values were approximately matched by Klejment and Rosinski (2008) with 1136 kJ/kg for municipal waste composting. More recently Antizar-Ladislao et al. (2010) were able to obtain a maximum of 6000 kJ/kg/day for green waste, industrial sludge and liquid waste.

Aside from obtaining useful energy for other purposes, it may be beneficial to the composting process to remove excessive heat. Large composting cells have lower surface to volume to ratios therefore allowing for excessive temperatures in the composting mass. Heat extraction could help in such cases. In addition, less energy would be spent on aeration for the cooling of large composting cells. The requirement for cooling air is reported to be 12 times greater than the chemical requirement for oxygen in biodegradation of the composting mass (Themelis, 2005).

The aim of this study is to observe the effect of different flow rates through a water cooled heat exchanger on energy values and compost temperature. In addition to this, the results from this pilot-scale experiment would help in the development of a computational model to standardize the process of compost heat removal.

MATERIALS AND METHODOLOGY

Pilot Scale experiment

The experimental site is located in the Swine complex at MacDonald campus, McGill University. In this experiment 12 barrels, 0.55 m in diameter and 0.89 m in height, are used with a copper tube running in a spiral through each unit. Nine of the barrels are separated by 3 different flow rates with 3 reps each, while 3 of the barrels will have a copper tube but zero flow rate and serve as control units. The flow rate is regulated with flow meters and the outlet temperature is monitored as well as the compost temperature within the barrels with the help of instrumentation connected to a data logger. It is important that the highest flow rate does not exceed 1L/min in order to not compromise aerobic digestion. Water flow will only be initiated when compost temperatures reach the thermophilic stage (~45°C). This follows results from Viel et al, whom found that starting heat extraction after the onset of thermophilic temperatures prolonged this stage instead of curtailing it. The compost composition is a mixture of animal manure and wood chips as a bulking agent.

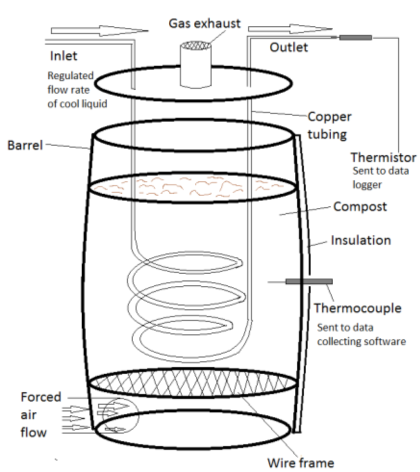

Fig 1. Pilot scale schematic

Fig 2. Composting barrels

Fig 3. Composting barrels

Fig 4. Copper tube heat exchanger

Heat Balance

In order to simplify the calculations for a heat balance the focus will be on the thermophilic stage as a steady state process in which all the heat losses and gains are accounted for. Therefore the sum of the various heats lost through the vapor at the top of the barrels, the heat lost through conduction at the walls and that lost through extraction by the heat exchanger would equal the total energy produced by aerobic digestion within the compost mass. The goal in this case is to relate the flow rate to the heat stored within the compost mass.

Computational Model

The model used in this experiment is based on a model developed by Courvoisier et al (2012). The main alteration to the model was to develop a 3D model from the original 2D model while using the same fundamental equations, with the Finite Element Modeling package, Comsol™. To model the heat extraction, the pipe flow module withing Comsol™ is used to model the copper tube heat exchanger. The basis of this model is centered on the growth of biomass as developed by (Stombaugh & Nokes 1996). The equation describing this growth is

$$\frac{dX}{dt} = (\mu - k_d)X \qquad (1)$$

where X is the concentration of biomass (kgX m^{-3}), μ is the growth factor (s^{-1}) and k_d is the proportion of death within the population per unit time (s^{-1}). In this model μ, the growth rate is affected by impact parameters such as temperature, oxygen content, moisture content and substrate concentration. This means that equations governing these individual parameters all have an effect on the concentration of microorganisms, and therefore the heat released within the compost mass. Results from the pilot scale experiment would be useful in developing and validating the model.

DISCUSSION

Although work has been done to obtain energy from the composting process, less common are precise studies investigating the proportion of heat that can be removed from the compost in relation to the mass of organic matter. In addition to this, for methods that involve a heat exchanger system, little in the literature measures the flow rates required to extract satisfactory heat without compromising the process. This study will aim to standardize protocols in this heat extraction method.

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