International Journal of Heat and Mass Transfer 75 (2014) 362–367

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Estimating thermal balance during composting of swine manure and wheat straw: A simulation method

Yongjiang Wang, Guangqun Huang, Anqi Zhang, Lujia Han *, Jinyi Ge

China Agricultural University, College of Engineering, 17 Qinghuadonglu St., 100083 Beijing, PR China

ARTICLE INFO

Article history:
Received 13 July 2012
Received in revised form 16 August 2013
Accepted 31 March 2014

Keywords:
Composting process
Thermal balance
Decomposition kinetics

ABSTRACT

Thermal balance model for composting process was developed to determine variations of heat loss components (conduction, convection and latent heat loss) during the process. Substrate decomposition was also modeled in order to measure biological heat production. Latent heat of water evaporation was predicted with absolute moisture content of outlet gases. Estimation of organics degradation was developed with a reaction kinetics structure of previous work. Lab scale experiments were carried out to verify the model. Simulation results were consistent with experimental data. The model could be a useful tool to analysis thermal balance process and to detect the efficiency of insulation layer during the composting.

1. Introduction

Composting is a heat production and loss process under aerobic conditions from the point of thermal engineering. During composting, microorganisms degrade organic matter into composting products, which can be used as soil amendment or organic fertilizer [1,2]. A considerable amount of energy is produced during the process to heat the waste layer to a certain temperature for sanitation. Therefore, temperature is one of the most important composting factors. The prediction of thermal balance of composting process is important in understanding composting dynamics and providing rational temperature control [3]. Thermal balance components during composting process include biological heat production, latent heat loss of water evaporation, sensible heat of inlet and outlet gases, and sensible heat of composting materials and reactor [4]. While several previous studies have analyzed the thermal production and loss processes during composting of various substrates, their results were not in agreement [3,5–11]. Generally, thermal balance process could be different depending on reactor scales. To be specific, heat production and latent heat loss were reported to be the most significant terms of heat balance process for full-scale systems [5–7]. However, conductive heat loss from surface of reactor walls, which could be more significant in smaller scale reactor [10], was usually estimated too [3,5,8,9]. In one study, wall conduction was reported to be the largest heat loss in a laboratory-scale composting reactor [5]. In a windrow type composting system, Robinzon et al. [11] reported that the latent heat of water evaporation contributed to the largest portion of heat loss, followed by radiation, and finally by convection. Ahn [3] conducted a thermal balance experiment to investigate the influence of different aeration rates and found that the evaporation heat loss was the major heat loss, but forced convection and conduction also played an important role in the heat balance process. Radiation loss was less than 5% which was pretty different from an open windrow situation reported by Robinzon et al. [11]. Vlyssides et al. [12] presented an integrated mathematical model for composting of wastewater and agricultural solid waste, which indicated that the evolution of bio-reactions heat, the loss by conduction from the surface and heat flow via exhaust air, intake air, and wastewater were major components of the energy balance process. In order to determine the temperature range feasible for compost cooling, Klejment and Rosiński [8] conducted an experiment to measure the thermal properties of composting materials. Although lots of works had been done to measure thermal balance process of composting, the results were quite different from each other. In addition, the previous studies also fail to understand thermal balance of composting process as a system.

Composting models supply a method to dynamically understand the thermal balance process as a system [1,4]. With simulation results, variations of different thermal balance components could be monitored during the whole composting process, instead of just giving an overall data that indicated which thermal balance component was significant.

This study was carried out with the use of a simulation method to analyze the thermal balance of composting process. Thermal balance models were developed to measure variations of heat loss

---

* Corresponding author. Address: China Agricultural University (East Campus), Box 191, Beijing 100083, China. Tel.: +86 10 6273 6313; fax: +86 10 6273 6778.

E-mail address: hanlj@cau.edu.cn (L. Han).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.03.083
0017-9310/

components during the whole composting process. In addition, decomposition kinetics was introduced to measure biological heat production. Laboratory scale experiments were conducted and data was collected to verify the model. In an attempt to understand the thermal balance processes as a dynamic system, this study also tried to answer the influence of an insulation layer on the thermal balance. For further study, thermal balance analysis in this study might contribute to provide the basis for recommending a reasonable coefficient of heat insulation as well as giving advices to operate a cooling system for composting process.

2. Materials and methods

2.1. Model description

The model used for the laboratory scale composting reactor system was based on fundamental principal of physical and biochemical reaction terms: substrate decomposition kinetics, heat balance mechanisms of mass and heat transfer. Composting substrate was assumed to be made up of biodegradable volatile solids (BVS), non-biodegradable volatile solids (NBVS), inorganic components and water [1]. Based on previous study, a new dynamic structured model for BVS degradation was introduced in this work [13]. Biologically generated heat was measured by multiplying the changes of BVS and the combustion heat of the substrate. Output terms of thermal balance in composting models included conductive heat loss, convective heat loss and latent heat of evaporation.

The models were performed and calculated by STELLA®. A switch object was introduced to turn insulation layer on or off in the thermal balance model based on the software platform. The heat transfer coefficient and the area of reactor walls were assigned to the switch button. The thermal balance model could be run with or without insulation layer to analyze the effect of conduction on the composting process.

Several assumptions and simplifications were made in the process of model development. Mass flow rate of air entering the reactor was equal to 80% of that for the outlet. Composting substrate, water and water vapor had the same temperature. The condenser of the composting reactor turned 20% of the steam within outlet gases into drops of water. Heat capacity of composting substrate was viewed as a dependent variable of BVS content. Oxygen and moisture content were configured with Graphical Input Devices built in the software to express their influences on BVS decomposition. The composting pile was a homogenous mixture without vertical variations for moisture content and temperature. Radiant heat loss was neglected from the energy balance components. Temperature was considered as the major effect on substrate decomposition rate in the situation without insulation. It was assumed that 60% of the initial volatile solid (VS) was biodegradable during the composting of swine manure and wheat straw based on results from previous work [2].

2.2. Reactor system

Lab-scale reactors with a working volume of approximately 12 L were employed in this study (Fig. 1). The main body of the reactor vessel was made of a steel tube, which had an internal diameter of 265 mm and a height of 390 mm. A perforated floor was fixed at the bottom of the reactor to keep composting substrates out of the air feeding pipe. Positive aeration was applied to the composting system with a blower and an air pipe. Insulation cap was constructed of wood board and plastic foam. The reactor was equipped with a water catcher to collect condensed water.

Two composting reactors were operated in the verifying experiment, one with insulation layer and the other one without insulation layer. Two additional reactors were employed specifically for measuring the volume and weight changes during the composting processes. Each of those two reactors was placed on separate platform scale to measure mass changes during the composting process. The composting process was operated without water feeding and same aeration rates were employed for all four reactors.

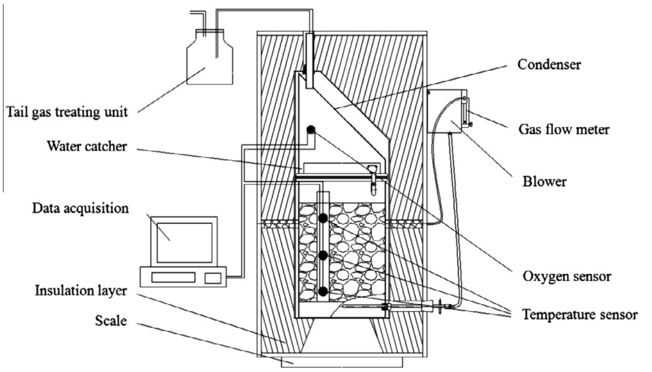

Fig. 1. Schematic diagram of the composting reactor.

2.3. Experimental design and measurement

A composting experiment that lasted for 14 days was performed to determine the impact of reactor insulation on composting process. Data collected was used to verify results from the model. While it normally took more than 14 days for a composting process to reach completion, significant substrate degradation, temperature fluctuations and oxygen consumption were observed during the first two weeks of composting in previous experiments. Degradation rate was observed to slow down considerably after the first two weeks of composting. Therefore, an experimental period of 14 days was chosen and data were monitored and recorded to verify the developed model.

Swine manure and wheat straw were mixed with mass ratio of 1:0.08 in order to gain proper initial moisture content, free air space and C/N. The initial moisture content of composting substrate was adjusted to approximately 65%. Continuous aeration was employed and temperature was considered as the key factor to set the air flow rate. Temperature was monitored by Pt 100 sensors and data was collected and documented by a programmed data acquisition system (DT85, DataTaker Pty Co., Ltd., Australia). Oxygen content was obtained by an oxygen analyzer (OMS-B, CEGT Science & Technology Co., Ltd, Beijing, P.R. China). The mass of the composting vessel was measured using a scale (SEP-120A, Shangzhun Weighing Apparatus Electronic Co., Ltd., Xiamen, P.R. China). The combustion heat of composting samples was measured by a bomb calorimeter (Calorimeter A1200DDEE, Parr Instrument Company, USA). Measurement of air flow rate was carried out with a gas flow meter (RK-1650, Kojima Instrument Inc., Japan). Dry matter content and volatile solids content were measured based on the test method for examination of composting and compost [14].

2.4. Substrate kinetics

Modeling of organic matter dynamics was critical to biological heat production [1]. A number of substrate degradation types have been discussed in previous studies [15–17]. Based on the work of Petric and Selimbasic [13], a new dynamic structured model for substrate kinetics during aerobic composting process was developed in this work. The composting solids were assumed to be made