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Assessing thermal conductivity of composting reactor with attention on varying thermal resistance between compost and the inner surface

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Dynamic estimation of heat transfer through composting reactor wall was crucial for insulating design and maintaining a sanitary temperature. A model, incorporating conductive, convective and radiative heat transfer mechanisms, was developed in this paper to provide thermal resistance calculations for composting reactor wall. The mechanism of thermal transfer from compost to inner surface of structural layer, as a first step of heat loss, was important for improving insulation performance, which was divided into conduction and convection and discussed specifically in this study. It was found decreasing conductive resistance was responsible for the drop of insulation between compost and reactor wall. Increasing compost porosity or manufacturing a curved surface, decreasing the contact area of compost and the reactor wall, might improve the insulation performance. Upon modeling of heat transfers from compost to ambient environment, the study yielded a condensed and simplified model that could be used to conduct thermal resistance analysis for composting reactor. With theoretical derivations and a case application, the model was applicable for both dynamic estimation and typical composting scenario.

1. Introduction

Reactor systems make composting process easier to control in terms of temperature, moisture content, gas emission, and compost quality (Haug, 1993; Mason and Milke, 2005; Orthodoxou et al., 2015). They have attracted more attention compared to static pile or windrow systems in recent years, especially in heavily populated areas. Heat transfer process is crucial when it comes to the design of composting reactors (Ahn et al., 2007; Ghaly et al., 2006; Wang et al., 2014). Heat transfer through reactor wall occurs through a complicated and non-steady state and involves biological heat production from organic degradation (Kaiser, 1996; Klejment and Rosiński, 2008). The heat transfer includes conductive, convective and radiative mechanisms. In order to make the heat transfer easier to be conducted in composting engineering, some model simplifications were introduced such as viewing the process as steady state, viewing the heat transfer coefficient as constant variable, or simply lumping different types of heat transfer coefficients as an overall parameter (Higgins and Walker, 2001; Lv, 2007; Van Lier et al., 1994; Zhang, 2006). However, it probably leads to a more accurate thermal estimation if more attention could be drawn upon the measurements of thermal resistance for each specific heat transfer mechanisms including conductive, convective, and radiative transfers (Mudhoo and Mohee, 2007). At the same time, an accurate method of estimating modeling parameters for heat resistance is needed for running reliable thermal-balancing simulations. Previous composting simulations on thermal balances involved heat transfer coefficient (Haug, 1993; Lv, 2007; Wang et al., 2014, 2016). Ensuring an accurate estimation of this parameter is an important step of using modeling and simulation to obtain information about how thermal transfer will behave without actually testing it in real life (Wang et al., 2016). A reliable and practical method of measuring thermal resistance for composting reactor requests separating considerations on each step of heat transfers through reactor wall.

Thermal balance for composting is a dynamic and interactive process (Vasiliadou et al., 2015; Woodford, 2009; Zhang et al., 2016). Biological heat production from substrate degradation is typically the thermal source that drives temperature variations. Heat losses include convective heat of outlet gases, latent heat of water evaporation and heat transfer through reactor wall (Mason, 2006). Intervention on a single component of thermal generation or losses can result in temperature fluctuation, and therefore puts impacts on biological kinetics. Previous study investigated the interactive process of thermal balance and pointed out that thermal transfer through reactor wall could possibly change temperature variations of composting process (Wang

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et al., 2016). Since the heat transfer through reactor wall is a dynamic process, it is necessary to develop a condensed model that connects the main heat transfer steps including conductive/convective transfers from compost to reactor wall, conductive transfers inside reactor wall, and convective/radiative transfers from reactor wall to ambient environment. The model should be used to not only understand the thermal transfers through reactor wall interactively but also supply a practical tool for insulation design. Overall heat transfer coefficient of a small-scale composter was experimentally measured in the lab with hot water to simulate compost as thermal source, which did not include the significant differences between compost/reactor-wall interface and water/reactor-wall interface (Lv, 2007). The contact characteristics between compost and inner surface of structural layer could affect the heat transfer considerably. Both conduction and convection occurred between compost and inner surface of structural layer since compost was a porous media. Higher porosity of compost could probably enhance convective heat transfer and reduce conductive heat transfer if the total heat flux was of certain level. Considering the shortages of assuming an infinite heat transfer coefficients at the surface boundary, a previous investigation (Erdogdu, 2008) believed that it was important to determine heat transfer coefficients simultaneously during the thermal-transfer processes. It was only possible to consider the coefficient simultaneously with considerations on varying compost physical condition such as moisture content and free air space. Temperature and moisture content were relevant to thermal conductivity of compost according to previous studies (Chen and Wu, 2005; Van Lier et al., 1994). Overall heat transfer coefficients in organic substrate composting experiments were determined for PVC drum composters (Mudhoo and Mohee, 2007). It was reported that the coefficients for day 0–3 were much larger than the values after day 3, indicating that the temperature of composter had an influence on heat transfer which however was not theoretically investigated in this study. Besides the insulation ability of reactor wall, it seems physical conditions of compost can affect heat transfer through reactor wall. However, such a model that estimates thermal transfers with physical conditions of compost was not comprehensively addressed.

The objectives of this study were: (1) to assess the heat transport through composting reactor wall by developing a generalized thermal transfer model; (2) to include separate measurements of conductive and convective thermal resistances between compost and structural layer so that thermal models could be derived to include physical conditions of compost; and (3) to supply a case study for determining thermal resistance or heat transfer coefficient to meet the specific need of parameter estimation for typical composting situations.

2. Methods

2.1. Description of heat transfer through the wall of composting reactor

Fig. 1 illustrates the reactor features and geometry considered in this paper. The shape of the reactor can be cuboid, cylindrical, or a combination of the two. Different reactor geometry leads to different calculations of heat transfer and should be discussed differently. A popular type of cylindrical reactor was selected in this paper as an example (Mason and Milke, 2005; Woodford, 2009). For reactor composting, convective heat is mainly transferred via gas flow and the reactor normally has a headspace that acts as an extra insulation layer, making conductive heat transfer through the top less significant. It should be noted that the gases in the headspace normally had a temperature higher than that of the

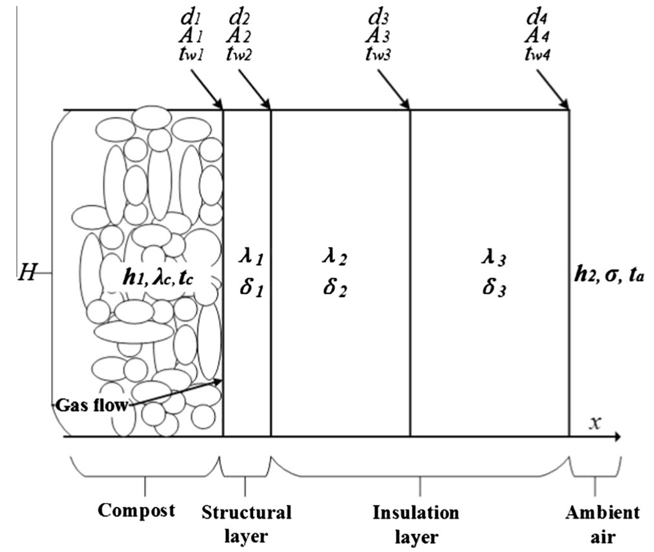

Fig. 1. Features and geometry of a composting reactor.

ambient air, making the conductive heat transfer between compost and the gases insignificant. However, gas flowing out the reactor contributed large portion of heat losses, which was accounted for convective heat loss due to aeration in this study. Horizontal heat transfer through side wall of the reactor was thus the main focus in this study.

Composting materials were considered as porous substrates that had a temperature of t_c and a porosity of γ, was piled to a height of H, had a diameter of d_1, and a surface area of A_1. Temperature of structural layer on the inside was t_{w1}. Note that both conductive heat transfer between compost and structural layer and convective heat transfer between gas flow and structural layer occurred at the same time, resulting in a slight temperature difference between t_c and t_{w1}. The conductive heat transfer coefficients for compost and convective heat transfer coefficients of composting gases and reactor inside wall were λ_c and h_1, respectively. Next to the composting materials on the right was a structural layer with a thickness of δ_1, a surface diameter of d_2, and a conductive heat transfer coefficient of λ_1. Normally, composting reactors need insulation layers to keep heat within the reactor. In this case, two different layers were considered, having thickness of δ_2 and δ_3, and conductive heat transfer coefficients of λ_2 and λ_3, respectively. The outside diameters and surface areas of insulation layers were d_2, d_3 and A_2, A_3, respectively.

It would make the estimation much simpler by considering uniform temperature for compost and inner surface of the structural layer. However, it is not the case when conductive thermal resistance between compost and structural layer and convective thermal resistance between gas and structural layer are considered. It is reasonable to expect that the convective thermal resistance is significant when the porosity of compost is controlled for proper aeration. Because the existence of controlled compost porosity, there are two comparable terms of thermal resistance between compost and the inner surface of reactor wall. It was speculated that the conductive resistance coefficient was less than the convective resistance coefficient between aeration gas and the inner surface of reactor wall under same temperature gradient. This study tried to separate the conductive and convective calculations of thermal resistance in an innovative manner. If the surface area between the compost and the inside surface of the structural layer was A_1, which could be calculated as $\pi \cdot d_1 \cdot H$, the assumption was made that $\gamma \cdot A_1$ was considered the convective surface area, while