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Characterization and modelling of the heat transfers in a pilot-scale reactor during composting under forced aeration

A. de Guardia *, C. Petiot, J.C. Benoist, C. Druilhe

Irstea/Cemagref, UR GERE, 17 Avenue de Cucillé, CS 64427, F-35044 Rennes, France
Université Européenne de Bretagne, F-35000 Rennes, France

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ABSTRACT

The paper focused on the modelling of the heat transfers during composting in a pilot-scale reactor under forced aeration. The model took into account the heat production and the transfers by evaporation, convection between material and gas crossing the material, conduction and surface convection between gas and material in bottom and upper parts of the reactor. The model was adjusted thanks to the measurements practised during fifteen composting experiments in which five organic wastes were, each, composted under three constant aeration rates. Heat production was considered proportional to oxygen consumption rate and the enthalpy per mole oxygen consumed was assumed constant. The convective heat transfer coefficients were determined on basis of the continuous measurements of the temperatures of both the lid and the bottom part of the reactor. The model allowed a satisfying prediction of the temperature of the composting material. In most cases, the mean absolute discard between the experimental and the simulated temperatures was inferior to 2.5 °C and the peaks of temperature occurred with less than 8 h delay. For the half of the experiments the temperature discard between the simulated peak and the experimental one was inferior to 5 °C. On basis of the calculation of a stoichiometric production of water through oxidation of the biodegradable organic matter, the simulation of water going out from material as vapour also allowed a rather satisfying prediction of the mass of water in final mixture. The influence of the aeration rate on every type of heat loss was characterized. Finally, the model was used to evaluate the impacts on material temperature caused by the change of the insulation thickness, the ambient temperature, take the lid away, the increase or the decrease of the mass of waste to compost.

1. Introduction

The material temperature is a key parameter of composting process, on one hand as a parameter and result of the biodegradation of organic matter and its progress towards stabilisation, and on the other, as a parameter of sanitization and drying. As a result, temperature is also a parameter of the nature and of the amount of gases emitted during composting. Thus, its prediction remains one main purpose of the scientists dealing with composting process. This purpose is common to composting plant managers eager to optimize the design of their plant and their process conditions.

Taking into account the complexity of the composting process and the variability of the waste characteristics, the accurate prediction of the material temperature as a function of time requires the development of mathematical models. Thus, many models were developed which also simulated oxygen consumption, mass, moisture and even gaseous emissions. They differ to each other from many aspects reviewed by Mason (2006). In spite of their high number, Mason (2006) claimed for the need of their improvement in rigour, accuracy, convenience and utility and, as result, for the acquisition of more experimental data. Mason (2006) also denounced their limitations regards the prediction of the material temperature. Indeed, the peak temperature and the date when it occurs were not simulated with accuracy in many models. More, the simulation of temperature was usually performed for few days i.e. a too short period compared to full-scale composting practice. For Ahn et al. (2007), “the energetics of the composting systems are generally not well known”. Indeed, both the characterization and the modelling of the heat generation and the heat transfers often remain rather inaccurate.

Recently, the calculation of the heat generation fluxes was assumed well known and the papers aimed to characterize the heat transfers. However, both the way the heat generation flux was calculated, and the values used, or fitted from modelling of heat transfers, for the heat generation coefficient, varied from one author to the others (Ahn et al., 2007; Bach et al., 1987; Bailey and Ollis, 1986; Ekinci et al., 2005; Harper et al., 1992; Haug, 1993; Kaiser, 1996; VanderGheynst et al., 1997; Weppen, 2001). Thus, Mason

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* Corresponding author at: Irstea/Cemagref, UR GERE, 17 Avenue de Cucillé, CS 64427, F-35044 Rennes, France. Tel.: +33 2 23 48 21 33; fax: +33 2 23 48 21 15.

E-mail address: amaury.de-guardia@irstea.fr (A. de Guardia).

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Nomenclature

A_B	surface of the bottom part of the reactor (m^2)
A_L	surface of the lid (m^2)
A_{MB}	exchange-surface between material and gas in the bottom part of the reactor (m^2)
A_{MU}	exchange-surface between material and gas in the upper part of the reactor (m^2)
Cp_{pDA}	specific heat of dry air (kJ/kg/°C)
Cp_{DM}	specific heat of dry material (kJ/kg/°C)
Cp_{SS}	specific heat of stainless steel (kJ/kg/°C)
Cp_W	specific heat of water (kJ/kg/°C)
Cp_{WV}	specific heat of water vapor (kJ/kg/°C)
DM	dry matter
FW	food waste
F_{DAE}	flux of dry air coming into the reactor (kg/h)
F_{VC}	flux of vapor condensed on the internal surface of the lid(kg/h)
F_{WVE}	flux of vapor coming into the reactor(kJ/h)
F_{WVS}	flux of vapor coming out from the material (kg/h)
F_{WVU}	flux of vapor in gas flow in the upper part of the reactor (kg/h)
GA	green algae
H_{ACC}	heat accumulation flux within the material (kJ/h)
H_{ACCB}	heat accumulation flux by the bottom part of the reactor (kJ/h)
H_{ACCL}	heat accumulation flux by the lid (kJ/h)
h_B	convective heat transfer coefficient between gas and material or gas and bottom in the bottom part of the reactor ($kJ/h/m^2/°C$)
H_{BIO}	heat flux produced by biodegradation (kJ/h)
h_{BIO}	heat released by microorganisms per mole of oxygen consumed (kJ/mol O_2)
H_{COND}	heat flux transferred from material to outside by conduction through reactor wall (kJ/h)
$H_{CONDENSATION}$	heat flux by condensation of vapor in contact with the lid (kJ/h)
$H_{CONV\ BAMB}$	heat flux transferred by surface convection between the external surface of the bottom of the reactor and ambient air (kJ/h)
$H_{CONV\ BGB}$	heat flux transferred by surface convection between the internal surface of the bottom and the gas in the bottom part of the reactor (kJ/h)
$H_{CONV\ ES}$	heat flux transferred through convection by sensible heat of dry air and vapor coming in the reactor and going out from the material (kJ/h)
$H_{CONV\ LAMB}$	heat flux transferred by surface convection between the external surface of the lid and ambient air (kJ/h)
$H_{CONV\ LGU}$	heat flux transferred by surface convection between the internal surface of the lid and the gas under the lid (kJ/h)
$H_{CONV\ MGB}$	heat flux transferred by surface convection between the composting material and gas in the bottom part of the reactor (kJ/h)
$H_{CONV\ MGU}$	heat flux transferred by surface convection between gas under the lid of the reactor and the composting material (kJ/h)
H_{EVAP}	heat flux transferred by evaporation (kJ/h)
h_O	convective heat transfer coefficient bet. external surface of the lid or the bottom and ambient air ($kJ/h/m^2/°C$)
h_U	convective heat transfer coefficient between gas and material or gas and lid in the upper part of the reactor ($kJ/h/m^2/°C$)
HW	household waste
k	conductivity of the insulation material (kJ/h/m/°C)
L	height of the reactor (m)
L_{EVAP}	latent heat of evaporation (kJ/kg water evaporated)
m_B	mass of the bottom part of the reactor (kg)
m_{DM}	mass of dry matter (kg)
m_L	mass of the lid (kg)
m_W	mass of water in the material (kg)
mW_{END}	mass of water in final mixture (kg)
mW_0	initial mass of water in initial mixture (kg)
OM	organic matter
OM_{BIO}	organic matter biodegraded during composting (kg)
OM0	initial organic matter content of waste (kg)
PSS	pig slaughterhouse sludge
R_{EXT}	external radius of the cylinder constituted by the insulation cover (m)
R_{INT}	internal radius of the cylinder constituted by the insulation cover (m)
r_{O2}	oxygen uptake rate (mol/h)
SPS	separated pig solids
T	composting material temperature (°C)
T_{AMB}	ambient temperature outside the reactor (°C)
T_B	temperature of the bottom part of the reactor (°C)
T_{GB}	temperature of the gas in the bottom part of the reactor (°C)
T_{GE}	temperature of the in-coming gas (°C)
T_{GU}	temperature of the gas phase under the lid(°C)
T_L	temperature of the lid (°C)
V_S	vapor content in saturated gas (kg water/kg dry air)
W_{ACC}	water accumulated (kg)
W_{BIO}	theoretical production of metabolic water (kg)
WC	wood chips
W_{LEACH}	water went out as leachates (kg)
W_{SUP}	water supplied when turning (kg)
W_{VE}	water came into the reactor as vapor (kg)
W_{VS}	water went out from material as vapor(kg)

(2006) reported that the heat generation coefficient varied between 17.8 and 24.7 kJ/g DM removed and between 304 and 448 kJ/mole O_2 consumed. Such variations can justify since the enthalpy of formation and the stoichiometry of bio-oxidation of every waste may depend on its biochemical composition. However, as mentioned above, the heat release is often calculated on basis of thermal balance assuming heat transfers are valid whereas determine heat transfer coefficients is rather complex and that uncertainties regards heat transfers still remain. Thus, until any specific experiment is performed in order to determine with accuracy the heat generation coefficient, the data reported by Bailey and Ollis (1986) and in agreement with heat released by electron exchange theory, i.e. 440 kJ/mole O_2 consumed, seem the most relevant.

Concerning heat transfers, these were studied by many authors as function of the size of the reactor. Most of the data published in literature were summarized by (Mason and Milke, 2005a). In windrow, Robinzon et al. (2000) estimated losses by evaporation, radiation and convection to respectively 70, 20 and 10%. Thus, natural convection including evaporation and transfers between composting material and gas surrounding material were recognized as the main contributors to heat loss in detriment of radiation (Moraga et al., 2009; Weppen, 2001). Moraga et al. (2009) also studied the influences of size and shape of windrow upon both heat losses, by convection and radiation, and material temperature. In full-scale reactors, Bach et al. (1987) and Weppen (2001) estimated losses by evaporation to more than 75% whereas losses from walls were estimated lower than 10%. Sensible heating of air