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Full Length Research Paper

Design of pilot device for municipal solid waste composting

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A mathematical model was developed for static composting process of municipal solid waste (MSW) based on the thermodynamics, kinetics of microbial growth, and hydrodynamics. A pilot scale aerobic ferment device was designed without leachate and malodor discharging. Its reasonable size, leachate collecting and recycling system, air distributing, and malodor recycling system were determined by the model and local conditions. The device was of great significance to study the theory, optimize composting parameters, and to instruct the designing of full scale device in the future.

Key words: Municipal solid waste (MSW), aerobic composting, experiment device, design, leachate, malodor.

INTRODUCTION

Rapid urbanization and constant growth of urban population have led to a dramatic increase in municipal solid waste (MSW) production, which has a crucial socio-economic and environmental impact, especially in the recent 15 years in China (Juho and Teemu, 2004). The composition of MSW has also changed greatly. In general, there has been an increase of organic and biodegradable compounds (Cheng et al., 2007; Hanc et al., 2011).

Composting is the aerobic biological decomposition of organic matter which is enhanced and accelerated for optimum microbial growth, and is defined as an environmentally sound method to biodegradable MSW (Gu et al., 2011). While aerobic composting has been used worldwide for many years, optimizing parameters affecting composting process is always an important problem to be resolved owing to a large composition variation in MSW. Thus, developing of experiment device of MSW aerobic composting is compulsory. At present, most composting research was taken by field experiment such as window system, and only a few took laboratory experiment (Das et al., 2011; Gu et al., 2011; Xi et al., 2005; Xiao et al., 2009; Zeng et al., 2006). Compared with field experiment, laboratory or pilot experiment is easier to control, spaces are smaller, and there are poorer disturbance under artificial climate.

Leachate and malodor could be produced during MSW aerobic composting process, similar with landfilling (Zeng et al., 2007a). Many composting plants and laboratory devices have no leachate and malodor recycle system now, so operators are always exposed to polluted environment (Masefumi et al., 2005). Many plants had built wastewater treatment system and malodor treatment system with a large cost. On the other hand, leachate from MSW composting is rich in microorganisms degrading the organic matter of MSW. Its recycling can accelerate the composting process (Zeng et al., 2007b). To save energy and promote waste recycling, this paper would design an aerobic composting system without waste water discharging and malodor emission.

THEORY MODEL OF STATIC AEROBIC COMPOST

Capacity of aerobic composting device

The composting process is driven by energy release which accompanies organic decomposition. Therefore, the energy or thermodynamic balance is largely determined by the extent of decomposition and its associated heat release (Ghaly et al., 2006; Zambra et al., 2011).

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$$\underset{\text{Organic Materials}}{\begin{pmatrix}\text{proteins}\\\text{amino acids}\\\text{lipids}\\\text{carbonhydrates}\\\text{cellulose}\\\text{lignin}\end{pmatrix}} + O_2 \xrightarrow{\text{Microorganisms}} \underset{\text{Humus or Compost}}{\begin{pmatrix}\text{cellulose}\\\text{lignin}\\\text{minerals}\end{pmatrix}} + CO_2 + H_2O + NH_3 + \text{new cells} + \text{heat}$$

Temperature is one of the key indicators in composting. The temperature at any point depends primarily on how much heat was being produced by microorganisms and how much is lost through aeration and surface cooling (Elango et al., 2009). A well constructed composting system can be heated up between 40 and 50℃ within two or three days. To ensure the suitable temperature, enough capacity of aerobic composting device is necessary for a successful composting process. But the aerobic composting is an open system, so heat is lost inevitably. Thus, prerequisite should follow the formula:

$$Q_{\text{in}} \geq Q_{\text{out, W}} + Q_{\text{out, E}} + Q_{\text{out, S}} + Q_{\text{out, A}} \qquad (1)$$

Where: Q_{in} = heat input (that is, heat from composting process, kJ), $Q_{out,W}$ = heat loss from water evaporation (kJ), $Q_{out,E}$ = heat loss to ambient environment (kJ), $Q_{out,S}$ = heat storage of composting substrate (kJ), and $Q_{out,A}$ = heat loss from aeration (kJ).

Heat balance

On the left side of Equation (1), Q_{in} is determined with thermodynamics of composting process, and is presented by Equation (2) as follows:

$$Q_{\text{in}} = h_1 \times a \times M_0 \times Y_0 \times \varepsilon \qquad (2)$$

Where: h_1 = heat quantity generated by unit dry organic matter (kJ/kg), a = content of dry matter in substrate (%), M_0 = initial mass of composting substrate (kg), Y_0= content of organic matter in substrate (%), and ε = degradation rate of organic matter (%).

On the right side, $Q_{out,W}$ is presented by Equation (3):

$$Q_{\text{out, W}} = h_2 \times (\omega_0 M_0 - \omega_1 M_1) + C_W \eta_W \times (\overline{T} - T_0) \qquad (3)$$

Where: h_2= potential heat of water evaporation (kJ/kg), ω_0 = initial water content in substrate (%), ω_1 = end water content in out compost (%), M_1= end mass of substrate (kg), C_w= heat capacity of water (kJ/(kg·℃)), η_W = water content in substrate (%), and T_0= initial temperature of substrate (℃), and $\overline{T}$ = average temperature of substrate during composting process (℃).

$Q_{out,E}$ is contributed by the total surface area of composting device. It can be carried out with Equations (4) and (5) as follows:

$$Q_{\text{out, E}} = \int_l K A_e (T - T_a) \mathrm{d}l \qquad (4)$$

$$K = \frac{1}{F} \sum \frac{F_n}{\frac{1}{\gamma_1} + \frac{B}{\delta} + \frac{1}{\gamma_2}} \qquad (5)$$

Where: l = length of composting device (m), K = total thermal conductivity coefficient of composting facilities (kJ/(m^2·h·℃)), A_e = thermal conductivity area (m^2), T = temperature of composting device (℃), T_a = temperature of ambient surroundings, stable during composting process (℃), F = total thermal dispersion area of compost facilities (m^2), F_n = total surface area of composting device (m^2), γ_1 = thermal conductivity coefficient between outside wall of device and ambient surroundings (kJ/(kg·℃)), γ_2 = thermal conductivity coefficient between inside wall of device and compost bulk (kJ/(kg·℃)), δ = thermal conductivity coefficient of device wall (kJ/(kg·℃)), and B = thickness of device wall (m).

Bio-organic MSW, that is, composting substrate, can be heated, and the temperature rise. $Q_{out,S}$ is calculated with the following formula:

$$Q_{\text{out, S}} = C_S M_0 \times (T - T_a) \qquad (6)$$

Where: C_s = heat capacity of composting substrate (kJ/(kg·℃))

And besides, high temperature air in substrate will be expelled and lose energy with aeration. $Q_{out,A}$ is determined by the following formula (Zambra et al., 2011):

$$Q_{\text{out, A}} = \int_0^{t_{\text{total}}} \beta C_a M_0 \mathrm{d}t \mathrm{d}(T(t) - T_a) = \int_0^{t_{\text{total}}} \beta C_a M_0 \mathrm{d}(T_a + \kappa t^{\psi_1} e^{\psi_2}) \mathrm{d}t \qquad (7)$$

Where: C_a = heat capacity of air (kJ/(m^3·K)), β = air volume per 1 kg composting substrate for one day (m^3/(d·kg substrate)), t_{total} = total time of composting process (d), and κ, ψ_1, ψ_2 = constant.

Mass balance

Composting substrate generally includes biodegradable volatile solids (BVS), non-biodegradable volatile solids (NBVS), ash, and water. Mass of NBVS and ash nearly stay stable during composting process, so the loss of composting substrate is equals to the sum of the loss of BVS and water. When degradation of substrate reaches a balance, the mass balance of BVS will be showed (Leejarkpai et al., 2011):

$$V\frac{dM_{BVS}}{dt} = M_{BVS} - M_{BVS,out} - ktM_{BVS} \quad (8)$$

Where: V = volume of composting substrate (m^3), M_{BVS} = mass of BVS (kg), $M_{BVS,out}$ = output mass of BVS (kg), and k = degradability coefficient (k is defined as the fraction of organics which are likely to degrade under composting conditions).

Aeration

Aeration volume

The control of aeration is largely dependent on the type of composting system employed which determines whether air is supplied by agitation, forced aeration, or a combination of the two. Forced aeration would be used in this research. Ideally, the air requirements of the microorganisms were dependent on the type of waste, the temperature, stage, and process conditions. The aeration will supply oxygen to microorganisms, extract heat, and remove water in substrate. So, volume of inputting air could be determined by requirement of oxygen supplying, heat extracting, and water removing. But in this paper, the aeration system was updated, as shown in Figure 1.

There is almost no air or malodor loss into the atmosphere during the composting process but a little fresh air would be added with sucking modes machine. The inputting air was determined with Equation (5):

$$\left|\frac{q}{M_0}\right|_{max} = \left|\frac{q}{M_0}\right|_{S,max} + \left(\frac{q}{M_0}\right)_H + \left(\frac{q}{M_0}\right)_W \quad (9)$$

$$\left|\frac{q}{M_0}\right|_{S,max} = \frac{\alpha_v So}{z_0 - z} \times \frac{\mu}{k_M} \quad (10)$$

$$k_M = (\sqrt{k_C Y} + 1)^2 \quad (11)$$

$$\left(\frac{q}{M_0}\right)_H = \frac{h_1}{h_2 \lambda j \omega + C_a \Delta T} \times \frac{\mu S_0}{k_M} \quad (12)$$

$$\left(\frac{q}{M_0}\right)_W = \frac{W_E}{w_0 - w_i} \quad (13)$$

Where: $\left|\frac{q}{M_0}\right|_{max}$ = the maximal aeration volume per 1 kg composting substrate (m^3/(kg·h)), $\left|\frac{q}{M_0}\right|_{S,max}$ = the maximal aeration volume for substrate degradation (m^3/(kg·h)), $\left(\frac{q}{M_0}\right)_H$ = aeration volume for heat extracting (m^3/(kg·h)), $\left(\frac{q}{M_0}\right)_W$ = aeration volume for water removing (m^3/ (kg·h)), λ = saturation ratio of vapor, α_v = oxygen volume per 1 kg substrate degradation (m^3/kg), z_0 = oxygen concentration of input air (%), z = oxygen concentration of output air (%), μ = the maximal specific growth rate (/h), j = saturate water vapor content (kg/Nm), S_0 = biodegradable concentration of initial substrate (%), W_E = water mass loss from aeration per 1 kg substrate, w_0 = moisture concentration of input air (%), w_i = moisture concentration of output air (%), and others were the same as the former.

Aeration pressure

To obtain successful compost, except for enough aeration volume, high aeration pressure is also of great necessity to ensure an aerobic process. The aeration pressure drop was determined with Moody formula and Ergun equation, given as follows:

$$\Delta P = \lambda_m \bullet \frac{h}{D} \bullet \frac{\rho v^2}{2} \quad (14)$$

$$\lambda_m = 2 \bullet \frac{1-\varphi}{\varphi^3}\left(\frac{150}{Re_m} + 1.75\right) \quad (15)$$

$$Re_m = \frac{D\rho v}{\eta} \bullet \frac{1}{1-\varphi} \quad (16)$$

Where: λ_m = friction loss factor, h= height of composting device (m), ρ = air density (kg/m^3), φ = free airspace ratio (%), η = average viscosity of air (Pa·s), v = air velocity (m/s), D = average particle size of substrate (m), and Re_m = amendment of Reynolds number.

PILOT DEVICE FOR MSW AEROBIC COMPOSTING

Schematic diagram of aerobic composting device

The schematic diagram for experiment device was

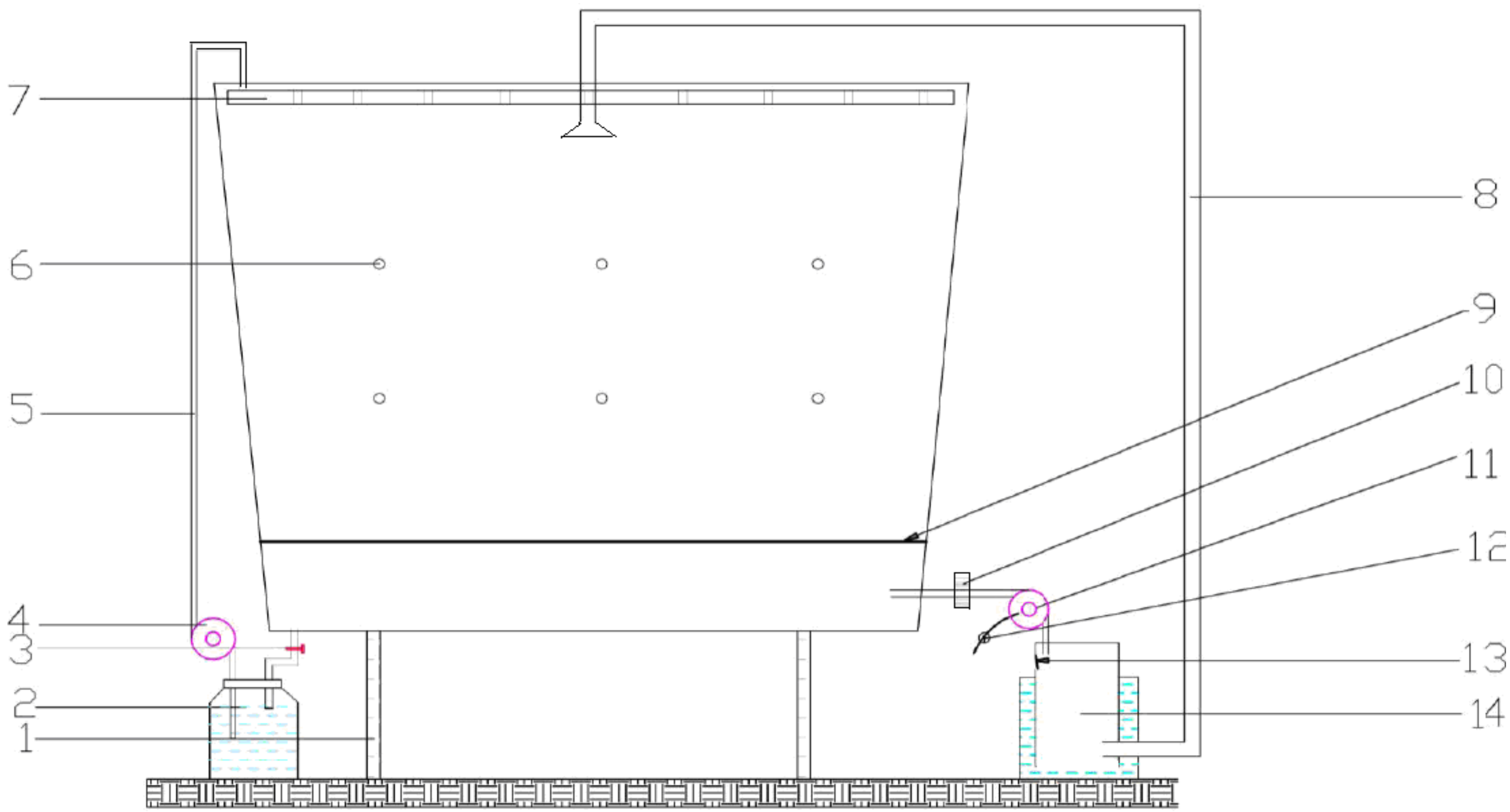

Figure 1. Schematic diagram of aerobic composting device; 1.support, 2.bucket, 3.valve, 4.pump, 5.water pipe, 6.hole for thermometer, 7.water spray, 8.wind pipe, 9.gas separation plate, 10. gas flowmeter, 11.fan, 12. time relay, 13.baffle,14. gas reservoir.

designed with thermal dynamics theory, as shown in Figure 1. The device was intended to accelerate the composting process by optimizing temperature, air flow, recycling leachate, and to verify the result of no waste discharge. The modes of aeration studied were up flow through PVC tubing filled gas chamber below a fine mesh screen near the bottom of the device. Six holes on the side wall of the device were used for temperature measurements. The leachate of the system was captured by bucket, and recycled by water pump every two days. It not only prevents the compost from drying out, but also prevents the removal of any microorganisms that are essential to the process. Initiative innovation of the device was that malodor generated from composting process could be collected by a reservoir and recycled by a fan at a frequency controlled by time relay. A baffle on the top of gas reservoir was designed to prevent malodor from releasing when fan did not work, and to add fresh air to the process when fan worked.

Dimensions of the aerobic composting device

According to thermodynamic and biochemistry dynamic theory, the ideal mathematical model were built for from Equations (1) to (16). Some parameters assumed are carried out as follows:

h_1 = 17.6 × 10^3 kJ/kg, h_2 = 2.44 × 10^3 kJ/kg, a = 45%, Y_0= 60%, ε = 30%, ω_0 = 55%, ω_1 = 40%, C_w = 4.2 kJ/kg, η_w = 0.55, T_a = T_0 = 293K, $\overline{T}$ = 318K, K = 0.6 kJ/(m^2·h·K), T = 333K, B = 0.04 m, C_s = 2.1 kJ/kg, β = 0.08 m^3/(d·kg), C_a = 1.4 kJ/(m^3·K), t_{total} = 12 d, $\kappa = 15$, $\psi_1 = 0.30$,$\psi_2 = 8.0\times10^{-3}$, μ = 0.1/h, z_0 = 18%, z_1 = 15%, K_cY = 12, S_0 = 0.3, α_v = 0.89 m^3/kg, j = 0.196, λ =1, h =0.5 m, ΔT = 40K, ρ =1.293 kg m^{-3},η = 1.81 × 10^{-4} Pa/S, v = 0.009 m/s, D = 0.06 m, and φ = 40%.

New formula was $\frac{\int_l A_e \mathrm{d}l}{M_0} < 34.6$.

Effective volume of the device was quadrangular frustum pyramid, with up length of 0.8 m, up width of 0.6 m, height of 0.5 m, down length of 0.7 m, and down width of 0.5 m. So the effective volume is 0.200 m^3. The total MSW is 90 kg for one time if the density of MSW is 0.45×10^3 kg/m^3. Therefore, the design is a suitable prerequisite of successful composting process.

$$\frac{\int_l A_e \mathrm{d}l}{M_0} = \frac{\int_0^{0.8} \frac{A}{B} \mathrm{d}l}{90} = \frac{\int_0^{0.8} \frac{2.13}{0.04} \mathrm{d}l}{90} = 0.47 < 34.6$$

According to Equations (4) and from Equations (9) to (16), the maximal aeration rate was 0.058 m^3/(kg·h), so, the total aeration of 90 kg composting substrate was 5.22 m^3/h. The aeration pressure drop was 200 mmH_2O. As the effect of das reservoir, pipe and separation plate is considered, the final aeration pressure was 1000 mmH_2O to reach forced blow.

CONCLUSIONS

In this research, a mathematical model ($\frac{\int_l A_e \mathrm{d}l}{M_0} < 34.6$) was developed to static composting process of MSW based on the thermodynamics kinetics of microbial growth and hydrodynamics. The model would provide an excellent tool for explaining and demonstrating the complex interactions in the composting process. With the model, a device for MSW aerobic composting was designed without leachate and malodor discharging. Additionally, the detail dimensions of the device were determined. The laboratory device would be of great significance to study the theory and parameters optimizing of composting, and to instruct the designing of field device in other countries.

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