Estimation of evaporation rate from composting toilet without energy supply

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Abstract

Keeping the moisture content of the toilet matrix in a proper range is the most important operational factor for the composting toilet. Water included in the matrix is removed by evaporation whose rates depend on matrix and air conditions. Since the composting toilet is expected to be installed into developing countries which require low energy consumption, we studied a composting toilet without energy supply for water evaporation. If no energy is supplied into the composting toilet, water evaporation rates vary widely due to various climate of developing countries and consequently water load allowed is restricted. Therefore the objective was to estimate allowable water load for the composting toilet without energy supply under specific matrix and air conditions. We performed lab-scale drying experiments using a wind tunnel to set up an evaporation model. As a result, water evaporation was characterized by constant rate period and falling rate period, summarized in a function of moisture content of the toilet matrix and air conditions. Subsequent full-scale experiments validated the model developed in this study. The model was then used to estimate allowable water load and showed allowable water load was highly correlated with air temperature and relative humidity (RH).

Keywords: allowable water load, composting toilet, constant evaporation rate, evaporation rate, falling evaporation rate, water content

1. Introduction

Composting toilet which stabilizes organic matter of human excreta is the promising technology for achieving nutrients recovery and reduction of water consumption. The composting toilet generally consists of the composting reactor, mixing fan and ventilation chimney. The most important factor for operating the composting toilet is keeping water content of the toilet matrix in a proper range which maintains high degradation rates.

In the early stage of the research, both urine and feces were treated by the composting toilet and due to high water content of urine heating system was adopted to promote water evaporation from the composting reactor to control water content. Heating system was proved to be efficient for evaporation with the efficiency between 0.6 and 1[1]. Composting toilet with heating system might be feasible in developed countries such as Japan, because energy supply network has been well established in developed countries. However, in developing countries, power generation and distribution system has not been enough so that reduction of energy consumption is required. To achieve low energy consumption, the urine diverting composting toilet without energy supply has been studied but control of water content still remained as challenges.

Since developing countries have various climate patterns; arid, tropical, continental, etc, evaporation whose rates change with the matrix condition widely depend on air conditions. Additionally, some regions have a habit of washing body with water, not paper, after toilet because of cultural reason. In these areas, water load is higher than the other areas resulting in high water content of the matrix but few studies which focused on water load have been performed. Therefore, the objective of this study was to estimate allowable water load for specified air and matrix condition to improve feasibility of the composting toilet in various areas.

2. Methods and Materials

2.1. Evaporation Mechanism

Evaporation of water from porous solids such as sawdust is typically divided into two phases; constant rate period and falling rate period. When drying materials contain abundant water, we can assume that evaporation rates do not change with water content of the drying materials and are described by mass transfer equation (1-1).

$$ER_{const} = k_L (H_{sat} - H_{air}) A \quad (1\text{-}1)$$

where, ER_{const} is constant evaporation rate, k_L is mass transfer coefficient, H_{sat} is saturated vapor amount of unit volume, H_{air} is vapor amount of unit volume at air phase, A is surface area.

If the water content becomes lower than the critical water content, evaporation rates begin to fall. In this period evaporation rates vary largely with the water content.

2.2. Preliminary experiment

Since it takes about two weeks to get new sawdust acclimatize to feces, on the other words, new sawdust does not decompose organic matter for the first two weeks, feces was loaded on the sawdust used in the experiment as the preliminary experiment. Swine feces was used for acclimatization and finally amount of feces which was accumulated into the sawdust was about 120 [g-feces/kg-drySD].

2.3. Laboratory-scale drying tests

Several laboratory-scale drying experiments using sawdust as the drying material was performed. A wind tunnel with rectangular cross-sectional area was used as the experimental device. During each experiment, experimental conditions; air flow rate, air temperature, air relative humidity(RH) and the thickness of the sawdust was kept constant and the water content of the sawdust was adjusted to 3 [g-water/g-total] at the beginning of each operation.

Drying tests at different air temperature and air RH was conducted with 2 [m/s] of air flow rate; 20, 25, 30 [℃] and 65, 80 [%] were selected as experimental conditions for air temperature and RH, respectively. Additionally, drying tests with different air flow rate was performed. Material weight change with time was measured constantly until the weight change of the sawdust was not observable for at least 20 minutes.

2.4. Full-scale drying tests

Drying experiments using an actual composting toilet (seiwa-denko) designed for one person was carried out to validate the evaporation model. In the full-scale experiments, air conditions were not controlled while ventilation rate was set at 0.16[m/s] to maintain air flow constant. Initial water content of the sawdust was the same as that of the lab-scale experiments. Feces load which was considered as the experimental parameter in the full-scale experiments was set at 0, 8.7[kg-f/kg-dry] and was supplied at intervals of 1 day. The matrix was mixed every 1 hour and the material weight was observed until constant weight was obtained.

Table1 Experimental condition of the lab-scale experiment

Air flow rate[m/s]	Air temperature[℃]	Air relative humidity[%]
2	20	65
		80
	25	65
		80
	30	65
		80
3	25	65
4.5	25	65

Table2 Experimental condition of the full-scale experiment

Air flow rate[m/s]	Feces load[kg-feces/kg-drysawdust]
0.16	0
	8.7

3. Results and Discussion

3.1. Modeling of evaporation from composting toilet

Drying rate profiles of the lab-scale experiment well followed drying theory: that is, the profiles were characterized by constant rate period and falling rate period (Fig1). In addition, constant evaporation rates observed in the lab-scale experiment were proportional to the difference of vapor amount per unit volume, which supported that constant evaporation rate is described by mass transfer equation. Fig2 suggested that mass transfer coefficient was expressed as a function of Reynolds number: equation (1-2) was developed in this study as the relationship between mass transfer coefficient and Reynolds number[2)]. Mass transfer coefficient was expressed in dimensionless form. The least square approach was applied to determine the relationship between mass transfer coefficient and Reynolds number.

$$Sh = 0.32\,\mathrm{Re}^{0.55} \quad (1\text{-}2)$$

where, Sh is Sherwood number, Re is Reynolds number.

As to the falling rate period, evaporation rates were summarized as a linear function of water content of the sawdust, which is shown in Fig3. For generalization, evaporation rates were normalized and expressed by the equation (1-3). All values of the critical water content obtained from the lab-scale experiment were in a certain range whose difference of the maximum value and minimum value was negligible for practical implication.

$$\frac{ER}{ERconst} = 0.48X - 0.18 \quad (1\text{-}3)$$

where, ER is evaporation rate, ERconst is constant evaporation rate, X is water content of the sawdust.

3.2. Validation of the model for water evaporation

Fig4 showed that the result of the evaporation experiment using the actual composting toilet was in agreement with the result of the lab-scale experiment, indicating evaporation model for constant evaporation rates developed from the wind tunnel drying test can be extended to the actual composting toilet with relatively low Reynolds number. As shown in Fig5, The model for falling rates which was established in the prior lab-scale experiment, Eq (1-3), is applicable to the composting toilet. Modification, however, should be implemented on the intercept which describes the effect of mixing on the evaporation rates. The critical water content varies due to drying specimen, shapes of composting reactors, location of the ventilation chimney etc but the range of the fluctuation of the critical water content is acceptable for estimation of evaporation rates from composting toilet. Accordingly, the critical water content for 24 [times/day] of mixing frequency derived from this study can be widely applied as the general value of the critical water content of composting toilet. Heat of reaction released from biological degradation of organic matter did not contribute to evaporation, as shown in Fig6.

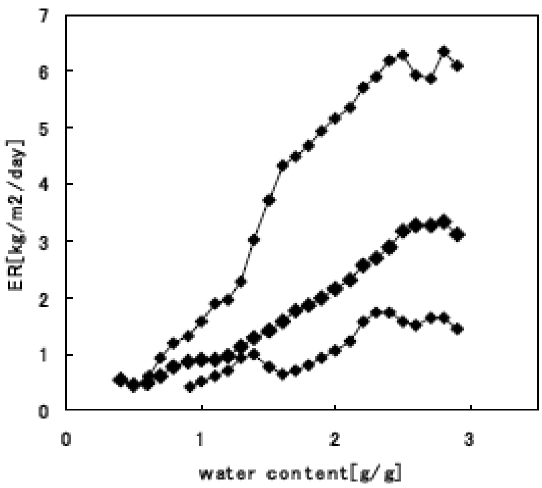

Fig1 Evaporation rate curves derived from the lab-scale experiment

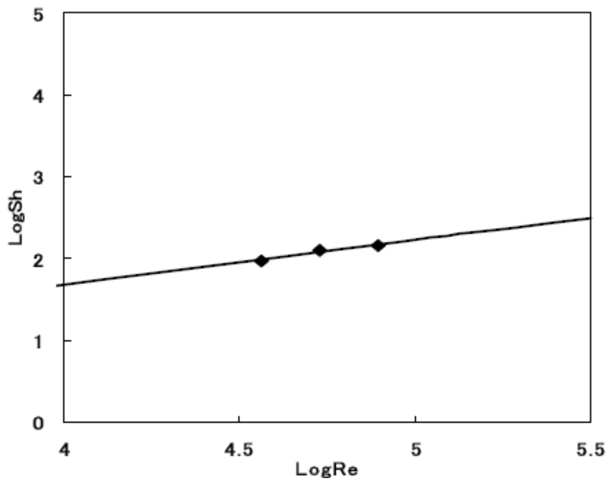

Fig2 The relationship between mass transfer coefficient and Re

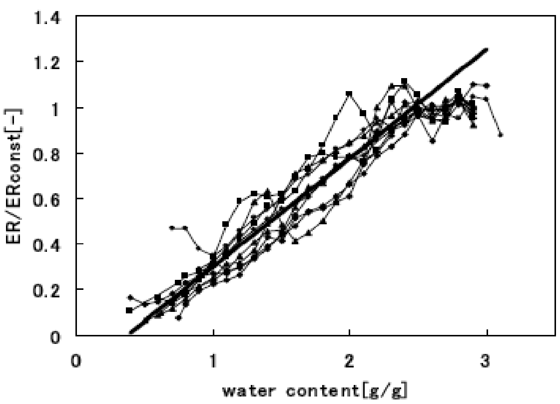

Fig3 Evaporation rate profiles of falling rates

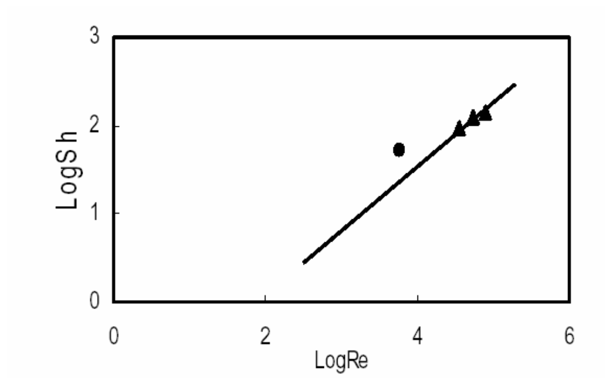

Fig4 Validation of evaporation model ▲:lab-scale experiment, ●:full-scale experiment, solid line: trend line

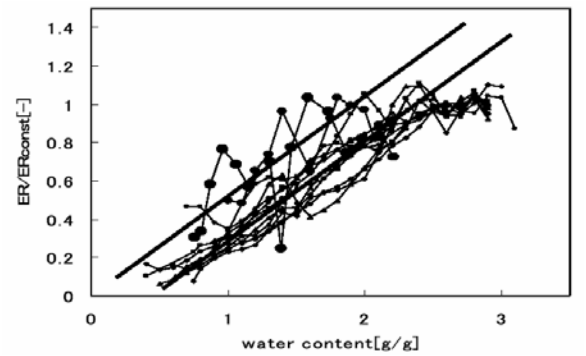

Fig5 Summarization of falling rate period

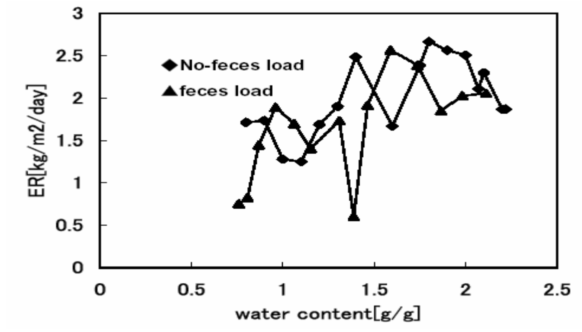

Fig6 Effect of biological reaction on water evaporation

Table3 The parameters adopted for simulating evaporation rate

Surface area[m^2]	Representative length[m]	Air flow rate[m/s]	water content[g/g]
0.21	0.55	0.16	1.8

3.3. Estimation of allowable water load

Applying the evaporation model developed in this study, evaporation rate of water from the composting toilet which was used in the evaporation experiment was estimated. Table3 shows the set parameters adopted for the simulation in terms of toilet properties such as surface area of the sawdust, air flow rate in the composting reactor and targeting water content. As a result, the diagram with contour lines representing evaporation rate was obtained (Fig7). Using this diagram, evaporation rate as water output is easily predicted. For example, evaporation rate of water from composting toilet in Sapporo Japan on August 2008 could be predicted to be approximately 0.12 [kg/day] from climate data of Sapporo[3)] Considering daily load of feces of an adult is about 130 [g/day][4)] and water content of human feces is approximately 80 %, water load for one day is evaluated as 104 [g/day/person]. Therefore the composting toilet used in this study is feasible in Sapporo.

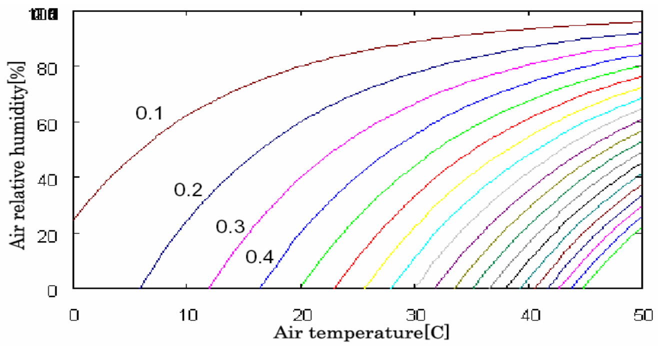

Fig7 Prediction of evaporation rate of water estimating by the model developed in this study. The unit of ER is [kg/day].

4. Conclusions

The objective of this study was to estimate allowable water load for composting toilet without energy supply under specified climate condition. As a result, Water evaporation was successfully modeled. Evaporation rates were characterized by constant rate period and falling rate period. Constant evaporation rate was expressed by mass transfer equation and mass transfer coefficient was described as the function of Reynolds number. Falling rate was approximated by the linear relationship with water content of the toilet matrix. The evaporation model developed in this study well agreed with the result of the full-scale experiment, giving good prediction of evaporation rates. Applying the evaporation model, allowable water load for specified air and matrix conditions was simulated.

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