



Energy analysis of composting toilet from full scale demonstration project on onsite differentiable treatment system

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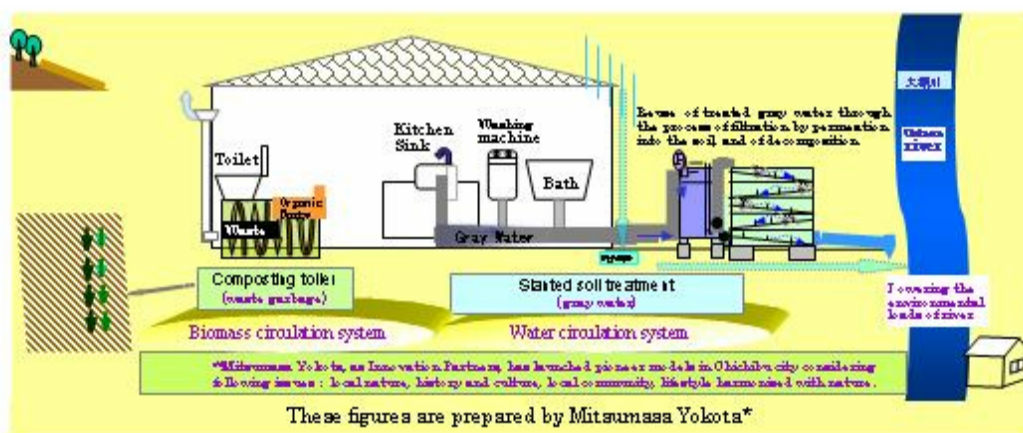
ABSTRACT

The composting toilet system is core facility of onsite differentiable treatment system and a kind of dry toilet that has a reactor under a toilet bowl. The reactor is filled with sawdust kept at around 60 °C by heating. The ventilation system supplies continuously fresh air from toilet bowl to exhaust pipe through over the reactor. Most of moisture and organic matter are removed from reactor by evaporation and biodegradation during their composting process, resulting in small accumulation of residual matter into the compost. However, it needs large energy supply for stable operation with heating. To improve this problem, we analyzed the energy structure of the toilet system. As a result, the drying rate and the power consumption were respectively around 3-4 kg/day and 15 MJ/day. Then the evaporation energy was calculated as 7-15 MJ/day. Next, enthalpies of inlet and outlet air per day were respectively 10-100 MJ/day and 20-112 MJ/day. Here, the difference between the enthalpies of inlet and outlet air was around 15 MJ/day. Finally, the chemical energy was estimated 0.5 MJ/day by discharge rate of faeces from two person. Therefore, the heat energy from power supply is equal to the difference of the enthalpies. 7-12 MJ/day of energy, which came from power supply, was used to drying and the other is just to heat-up the air. The heat efficiency for drying, which was defined as ratio of evaporation energy to energy consumption, was around 60-100 %, and independent of ventilation air flow rate.

INTRODUCTION

The Onsite Wastewater Differential Treatment System (OWDTS), we proposed [1], has a potential to realize a new social model, which is consisted by an environmentally friendly system naturally circulating water and material for reuse of treated water, and reutilization of organics and nutrients in wastewater. On the other hand, Yokota has

started producing an innovation model of sustainable sanitation systems on Chichibu-city in Japan to fruit “human- and nature-friendly sustainable sanitation system”, which is based on a catch line of “a social system putting emphasis on natural circulation especially water” and local characteristics, such as local nature, history, culture, communities and lifestyle harmonized with nature. So, a demonstration project was formed for excellent synergy between technical and political aspects [2]. The essence of this study is to share the vision to prepare the social system with mayor of Chichibu city, living people in the city and member of the research group. And then a pilot study has been performed to evaluate treatability, safety, economy and usability, as shown in Figure 1.



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Figure 1. Illustration of new sustainable sanitation system

In this system, waste and garbage are treated in a composting toilet system, while graywater, which is exhausted from drainage from kitchen, washing, bath, lavatory basin etc., is treated by a slanted soil treatment system, then discharged into a river. Here, it should be noted that black water occupies 44 % of organic matter, most of nitrogen and phosphorus in wastewater [3]. So, the black water treatment system is focused in this paper. The composting toilet system has a composting reactor under a toilet bowl, mixing mechanism, heater and ventilation system (Figure 2). The reactor is filled with sawdust kept at around 60 °C by heating [4]. The ventilation system supplies continuously fresh air from the toilet bowl to the exhaust pipe through over the reactor. Most of the moisture was removed from the reactor by evaporation, while the moisture content of the compost was kept around 60 % [5]. The organic matter was biodegraded during their composting process, resulting in a small accumulation of residual matter into the compost [6]. So, it can work long time without removing accumulated materials from the compost. The compost is finally returned into the firm land for a biomass cycle. However, it needs large energy supply for stable operation with heating.

The aims of this paper are to analyze the energy structure of this toilet system, to develop the index for energy consuming and to investigate the new policy for energy-saving operation to improve this problem.

METHODS

Figure 2 shows the measurement set-up for continuous monitoring. The measured items were the air temperature and humidity in inlet and outlet air, the moisture content of compost, the ventilation-air-flow rate and the power consumption of heater and whole system. In addition of these, the moisture content of compost is measured by gravimetric method of the sampled compost. Then, we calculated the following items from these data: items for input of energy were 1) the enthalpy of inlet air, 2) the chemical energy of waste and 3) the heat from power supply; those for output are 4) the enthalpy of outlet air and 5) the evaporation energy of dried water; and 6) heat accumulation into compost. The operation condition is summarized on Table 1.

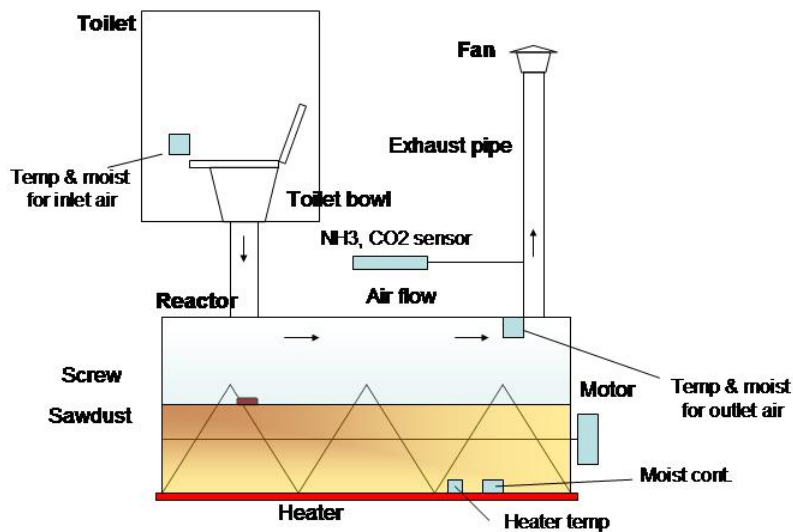


Figure 2. Illustration of composting toilet and monitoring set-up

The vapour pressure, P_w [Pa], and moisture amount in air of unit volume, W_w [kg/m³], are calculated from the temperature, T_a [K], and relative humidity, RH [-], using Sonntag equation [7].

$$P_w = e^{-6096.9385(T_a+273.15)^{-1} + 21.2409642 - 2.711193 \times 10^{-2}(T_a+273.15) + 1.673952 \times 10^{-5}(T_a+273.15)^2 + 2.433502 \ln[(T_a+273.15)]}$$

$$W_w = \frac{P_w}{R(T_a + 273.15)} M_{w_w} \cdot RH$$

where M_{w_w} [g/mol] is molecular weight of water and R [Pa m³/K mol] is gas constant.

Table 1. Operational conditions

	Date	Ventilation air flow rate [m ³ /h]	Heater temp. [°C]	Automatically-mixing interval [h]	Mixing time [min]
I	2005.5.9	60.00	45	2	3
II	2005.7.8	56.34	45	2	3
III	2005.8.23	42.42	45	2	3
IV	2005.9.6	50.94	45	2	3
V	2005.9.13	32.04	40	2	3
VI	2005.10.26	32.04	50	2	3
VII	2005.11.11	32.04	OFF	0.25	3
VIII	2005.11.22	32.04	50	2	3

Then, the drying rate, DW [g/min], is estimated from difference between moisture amount of inlet air and outlet air as follows:

$$DW = (W_{w, out} - W_{w, in}) F$$

where F [m³/min] is volumetric flow rate of ventilation air. The enthalpy, H_{air} [J/min], of both air flows is finally obtained as;

$$H_{air} = (1.006(T_a - 273.15) + (1.884(T_a - 273.15) + 2490)H_a) F_w$$

where H_a [kg-water/kg-dry air] is absolute humidity and F_w [kg-dry air/min] is mass flow rate of ventilation air. H_a and F_w are respectively calculated as follows:

$$H_a = 0.622 \frac{P_w \cdot RH}{101300 - P_w \cdot RH}$$

$$F_w = \frac{1.293}{1 + 0.00367T_a} F$$

Additionally, the second term of right side is latent heat of vaporization.

The energy flow rate, H_{heater} [J/min], from heater is calculated from power consumption of heater, Ph [W], using following equation.

$$H_{heater} = Ph * 60$$

We can get the energy generation by aerobic biodegradation of organic matter in waste, H_{react} [J], from COD in waste, S_{COD} [g-COD], by following equation [8].

$$H_{react} = 13600 \times S_{COD}$$

The energy accumulation into compost is yielded using following equation.

$$H_{accum} = \frac{4.18U + 0.266 + 0.000116(T - 273.15)_c}{1 + U}$$

where U [kg-water/kg-dry compost] is moisture content of compost and T_c [K] is temperature of compost.

RESULTS

Figure 3 respectively show the temperature and relative humidity of inlet and outlet air. We calculated the drying rate from this data as shown in Figure 4. The rate was then approximately 3-4 kg/day. Here, water injection into this system comes from cleaning water for toilet bowl and hand washing water besides moisture in waste. Then, we estimated daily water load to the system from the average daily number of usage as follows: The daily usage was estimated around 6.5 times per day from Figure 5. The amounts of water every usage for cleaning toilet bowl and washing hands were respectively 50 ml and 150 ml, while around 1 liter of urine was exhausted from one person per day according to discharge rate for one person [3]. Therefore, about 3.4 L of water was loaded into the reactor. We can consequently conclude that the estimated drying rate from monitoring approximately agree with calculated from base unit.

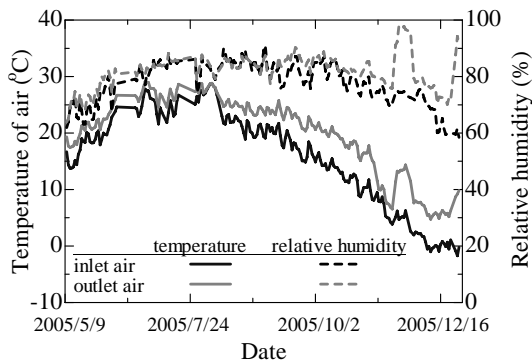


Figure 3. Time course of temperature and humidity of inlet and outlet air

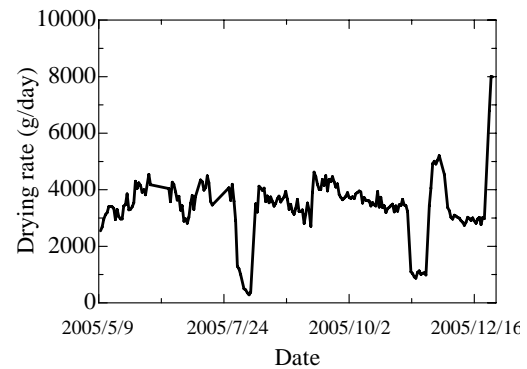


Figure 4. Time course of drying rate of compost

Figure 6 shows the evaluated amounts of energy a day for each item. The energies of inlet and outlet air energy, and the supplying rate from heater were respectively 25-100 MJ/day, 40-112 MJ/day and 15 MJ/day. The energy generation by aerobic biodegradation of organic matter in waste was estimated approximately 0.5 MJ/day using basic unit for excreting organic matter [9]. Here, the energy balance for the reactor is described by following equation.

$$H_{air, out} - H_{air, in} = H_{react} + H_{power} + H_{accum} + H_{loss}$$

where $H_{air, in}$ [MJ/day] is the inflow energy per day as inlet air, $H_{air, out}$ [MJ/day] is the outflow energy per day as outlet air, and H_{loss} [MJ/day] is heat loss. The difference between $H_{air, in}$ and $H_{air, out}$, and a typical energy balance are respectively shown in Figure 7 and 8. The difference, heat supply and heat generation is considered in following

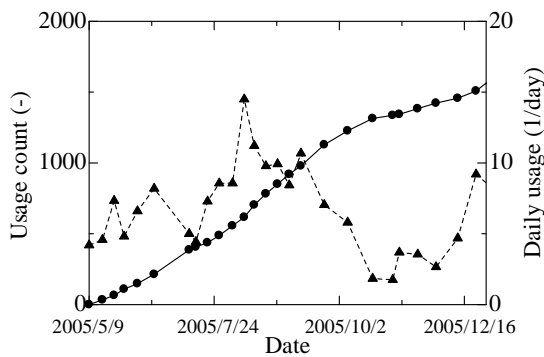


Figure 5. Daily usage of the toilet

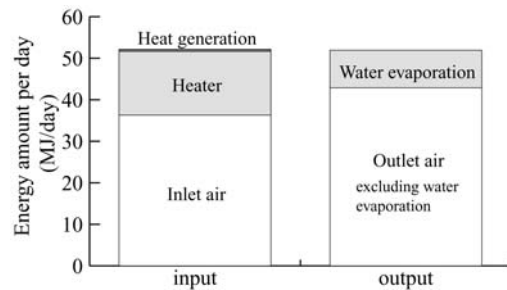


Figure 8. Typical energy balance of the toilet

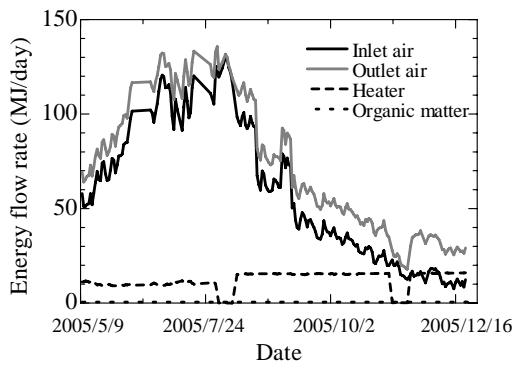


Figure 6. Progress of energy flow rate

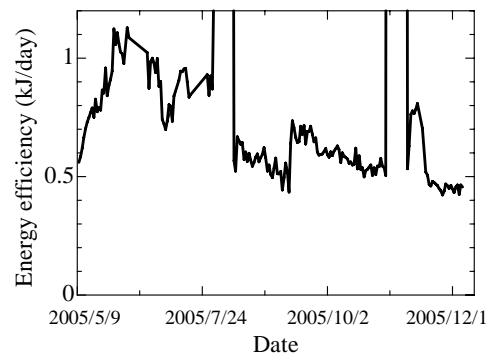


Figure 9. Energy efficiency

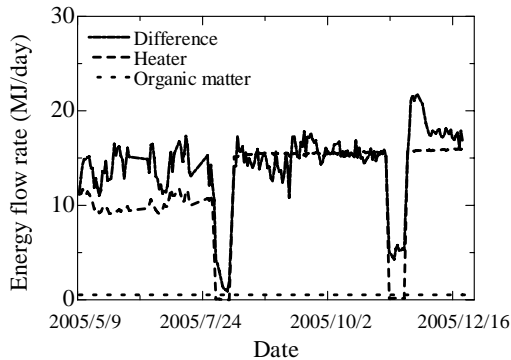


Figure 7. Energy flow of difference and heat supply

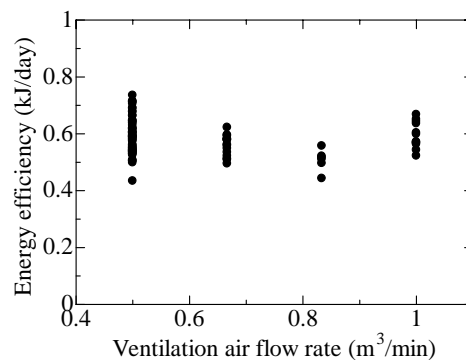


Figure 10. Effect of air flow rate on energy efficiency



discussion, because they were tremendously huge comparing with the others. The latent heat of vaporization calculated from drying rate is also shown in Figure 7 and 8. The difference was about 7-15MJ/day and agreed with heat energy, while other energy sources were negligible. Hence, the heat energy was consumed by vaporization of water and heat up the ventilation air. So, we defined heat efficiency as the ration of the latent heat to heat supply by heater, which is an index for effective energy consumption. The estimated heat efficiency is shown in Figure 9. The efficiency was from 0.6 to 1, therefore half or whole supplied heat was consumed for water evaporation.

Figure 10 shows the effect of ventilation air flow rate on energy efficiency. The efficiency was independent of the flow rate, also independent of the difference between inlet and outlet air, the latent heat, and heat energy. As a result, it might be inferred that the heat and water transfer was limiting process on the drying kinetics of compost.

DISCUSSION AND CONCLUSIONS

We investigated the energy structure of composting toilet system, which is the core facility of onsite differentiable treatment system, owing to requiring large energy supply for stable operation with heating. As a result, the drying rate and the power consumption were respectively around 3-4 kg/day and 15 MJ/day. The evaporation energy was calculated as 7-15 MJ/day. The difference between the enthalpies of inlet and outlet air was around 15 MJ/day. The chemical energy was estimated 0.5 MJ/day from basic unit. Therefore, the heat energy from power supply is equal to the difference of the enthalpies. 7-12 MJ/day of energy, which came from power supply, was used to drying and the other is just to heat-up the air. The heat efficiency for drying, which was defined as ratio of evaporation energy to energy consumption, was around 60%, and independent of ventilation air flow rate.

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