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Drying characteristics of sewage sludge

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Abstract−To obtain the drying rate of sewage sludge for use in design of a conductive indirect-heating dryer with agitation, the drying characteristics of sewage sludge from three different wastewater treatment plants were investigated with a thermogravimetric analyzer (TGA) in isothermal conditions. Temperature and sample mass were considered as experimental variables. The drying mechanism agreed well with the shrinking core model dominated by the kinetic rate. The activation energy of drying was 17.30 kJ/g mol. A rate equation was proposed for drying of sewage sludge.

Key words: Drying, Rate, Activation Energy, Sewage Sludge

INTRODUCTION

According to stringent environmental regulations, the production of sewage sludge from wastewater treatment plants has been continuously increasing worldwide [1,2]. The management of these growing amounts of sludge has become an important issue. Because of its high moisture content, the sewage sludge needs to be dried first for easier handling and transportation before application to use [3-10]. This obviously reduces the mass and volume of waste, and consequently, the cost for storage, handling and transport, and impact to the stability of the process that uses it. The constant rate drying period was found in drying of sewage sludge by microwave heating but not in conventional drying [4]. Wang and Li [6] investigated the drying rate of sewage sludge with a thermogravimetric analyzer, based on the principle of isothermal reaction kinetics. The drying kinetics was affected by drying temperature and sludge size. The suitable temperature of drying sewage sludge was near 125 °C [7]. Jiang et al. [8] investigated the thin layer drying behavior of sewage sludge in an indirect drying process over the temperature range of 80 °C to 150 °C. The activation energy of drying was found to be 29.56 kJ/g mol. Ultrasonic pretreatment could speed up evaporation of the free water in sludge surface, improve the drying efficiency, and help to end the drying stage with constant speed [9].

The choice of a proper type of dryer depends strongly on the physical and chemical characteristics of dried material. Various types of dryers have been developed for different kinds of material [11]. The conductive indirect-heating dryer with agitation is a good choice to dry various types of organic material like sewage sludge, which are initially sticky, form lumps before drying, but disintegrate into small pieces or particles during drying [12,13]. Inside the dryer is a particle bed consisting mostly of dried product particles that is agitated mechanically without any gas injection. Particles in the bed are moved vertically and horizontally by agitation. Outside heat for drying is supplied by conduction heat transfer through the dryer wall. The inner dryer wall, the heat transfer area, is rubbed constantly by moving dry particles and kept clean by that action. Therefore, heat is thereby conveyed efficiently from the wall to particles contacting the wall and then throughout the particle bed by convective motions of the particles. This behavior of the particle bed is similar to that of a fluidized bed and allows the feeding of wet and sticky material to the particle bed. Evaporated moisture and dried particles are discharged from the dryer by an induced-draft fan and a conveyor. Dryer pressure is maintained at about 50 Pa below atmospheric pressure, and dryer temperature is greater than 100 °C [12,13].

However, there are few studies on drying rate of sewage sludge that are suitable to use in designing the conductive indirect-heating dryer with agitation. The purpose of this study was to investigate isothermal drying characteristics of a sewage sludge using a thermogravimetric analyzer (TGA). To obtain drying characteristics in the condition similar to that of the conductive indirect-heating dryer with agitation, there was no gas injection into the TGA and effects of drying temperature and sample size at atmospheric pressure were considered as experimental variables.

EXPERIMENTAL

Isothermal drying characteristics were measured using a thermogravimetric analyzer (TGA) system with an electric heater as shown in Fig. 1. The TGA system consisted of a reactor part and a balance part. The reactor part was a vertical quartz tube with an electric heater. The reaction zone was in the heated quartz tube. The balance part included a balance (Explorer Pro, Ohaus Corporation) and a sample holder. The balance could weigh up to 210 g with an error of 10^{-4} g. The sample holder was made with stainless steel screen and hung down on a wire of K-type thermocouple. The balance part could be moved easily vertically. Initially, the balance part was separate from the reactor part, so the sample holder containing a sample was out of the reaction zone. The reaction zone was heated separately to a specified drying temperature. After the reaction zone reached

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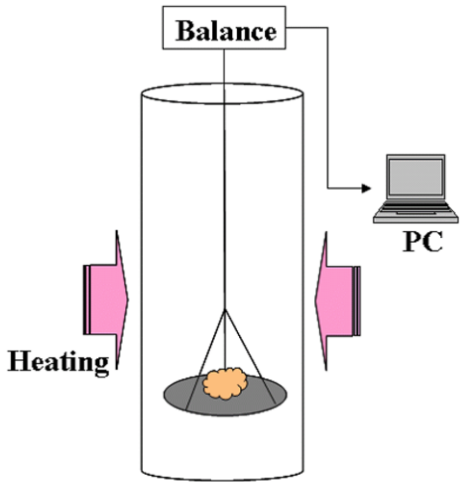

Fig. 1. Thermogravimetric analyzer system.

the drying temperature, the sample holder was inserted into the reaction zone by moving down the balance part in about 10 s. A K-type thermocouple placed just below the sample holder measured the drying temperature. Raw data such as variation of sample weight were stored in a pc. To simulate the condition of the dryer of Kim [12] and Choi et al. [13], no gas was injected into the TGA and the evaporated moisture was released at the exit by a hood system.

The test material was sewage sludge, an organic residue from municipal waste water treatment plants located three different cities (Jungrang in Seoul, Sungnam in Gyeonggi-do, Daejeon) in Korea, respectively. Table 1 summarizes properties of the sewage sludge. Proximate analysis indicated a weight ratio of the moisture about 80% (w.b.). The sample was molded into an approximately spherical shape. Drying temperature at atmospheric pressure was varied from 100 °C to 200 °C. The initial sample mass was varied from 0.25 g to 1 g. The relative humidity of the ambient air was determined via dry- and wet-bulb temperature measurements. The average ambient temperature was 295 K and the average relative humidity was 55% on the humidity chart, so the average vapor pressure was 1.44 kPa and the relative humidity was not greater than 1.4% at 100 °C. Therefore, the ambient gas humidity and the equilibrium moisture content of dried solid could be safely ignored for the experimental range.

RESULTS AND DISCUSSION

Fig. 2(a) shows trends of mass change during drying for an initial sample mass 0.5 g with varying drying temperatures. Sample mass decreased due to moisture evaporation during drying and finally leveled off once drying was completed. The fraction of mass loss

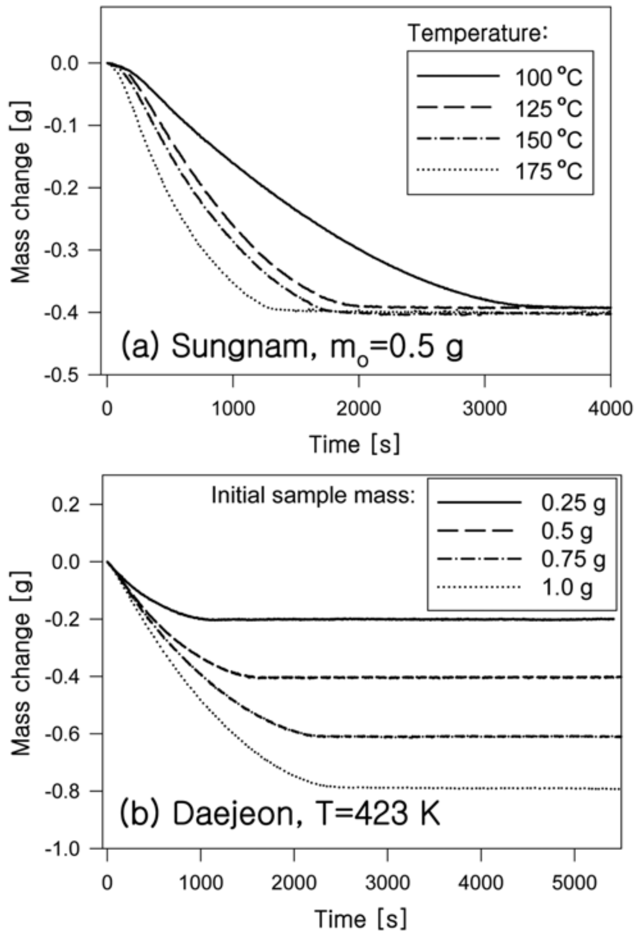

Fig. 2. Typical drying characteristics of sewage sludge (a) m_o=0.5 g, (b) T=423 K.

to the initial mass at temperature ≤200 °C agreed closely with the moisture fraction of the initial sample shown in Table 1. However, it exceeded appreciably the moisture fraction of the initial sample at 250 °C. This result indicates that the weight loss of the volatile matter by decomposition of organic matter is negligible at temperature ≤200 °C but appreciable at 250 °C [14,15]. Therefore, the result at temperature ≤200 °C was taken into consideration. It seemed that the drying rate increased while the sample was initially warming up. Subsequently, the drying rate had a falling-rate period without a constant-rate period [16]. Little surface moisture was observed in the initial sample, so it is believed to be responsible for the absence of the constant-rate period [4,15]. The increase of temperature resulted in an increased drying rate, which led to a decreased time for complete drying. Fig. 2(b) depicts trends of mass with initial sample mass as a variable and temperature fixed at 150 °C. All those

Table 1. Properties of sewage sludge

Name	Ultimate analysis (dry basis, wt%)				Proximate analysis (as received basis, wt%)				Higher heating value (kJ/kg)
	C	H	N	S	Moisture	Volatiles	Fixed carbon	Ash	
Daejeon	31.29	5.43	6.42	1.43	82.15	10.98	0.86	6.01	14090
Sungnam	32.02	4.58	5.27	1.02	79.93	14.45	2.30	3.31	13910
Jungrang	26.64	3.67	3.77	1.05	79.09	11.21	8.46	1.24	11100

trends for mass changes are similar to Fig. 2(a), but the time required for complete drying increases as the initial sample mass increases due to the increase in sample moisture.

In the present drying, heat is transferred from the gas phase to the inside of a sample by convection and conduction. Drying occurs first at the outer skin of the sample sphere, then the inner part. Moisture evaporated from the sample diffuses out to the bulk of gas phase through the pore of the dried solid layer, then through the gas film above the outer surface of the sample. The present drying mechanism is similar to that of the unreacted core model as a gas-solid reaction model that considers the zero order on gas reactant concentration and a solid particle of unchanging size. The unreacted core model has three possible rate-controlling steps: kinetic rate, diffusion of moisture vapor through gas film, and diffusion of moisture vapor through product layer [17]. When one of these steps is a dominant factor, we obtain the following relationship between time t and fractional conversion of drying X [17,15].

Kinetic controls:

$$t=\tau\{1-(1-X)^{1/3}\} \tag{1a}$$

$$\tau=\frac{\rho_B R_p}{k_s} \tag{1b}$$

Diffusion of moisture vapor through gas film controls:

$$t=\tau X \tag{2a}$$

$$\tau=\frac{\rho_B R_p}{3k_g C_{Bs}} \tag{2b}$$

Diffusion of moisture vapor through dried-layer controls:

$$t=\tau\{1-3(1-X)^{2/3}+2(1-X)\} \tag{3a}$$

$$\tau=\frac{\rho_B R_p^2}{6D_e C_{Bc}} \tag{3b}$$

In the above relationships, τ is the time required for complete drying of a sample, k_s is the drying rate per unit surface area of the undried spherical core, ρ_B is the initial water content per unit volume of a sample, k_g is the film mass transfer coefficient of moisture vapor, C_{Bs} is the moisture content of gas phase at sample surface, D_e is the effective diffusivity of moisture in dried solid layer, C_{Bc} is the moisture content of gas phase at radius of undried core, and R_p is the radius of an initial sample sphere. The fractional conversion of drying X and the radius of undried core r_c are determined as follows.

$$X=1-\left(\frac{r_c}{R_p}\right)^3=\frac{m_0-m}{m_0-m_\infty} \tag{4}$$

In Eq. (4), m_o is the initial sample mass, m is the sample mass at a time t, and m_∞ is the sample mass after complete drying. As an approximation, the radius of the sample sphere was considered not to change during drying.

Fig. 3 compares three possible rate-controlling steps by applying Eqs. (1)-(3) to a measured set of time and fractional conversion of drying. Each line plot for a controlling step was built by the measured data. For a controlling step, its relationship appears to be linear with its τ as a slope in Fig. 3. Since the plot with kinetic rate as the rate-controlling step (Eq. (1a)) showed better linearity than the other two plots, we concluded that the kinetic rate ruled the present drying mechanism of sewage sludge.

Fig. 4 shows the trend of Eq. (1a) based on the data measured in the present study as temperature and initial sample mass are varied. The slope of the plot in Fig. 4 indicates that τ increases as the initial sample mass increases or temperature decreases. The heat transfer rate, and the vapor pressure of moisture and the mass transfer rate of moisture vapor in the dried layer increase with an increase of temperature [18,19]. As mass, i.e., radius, of the initial sample

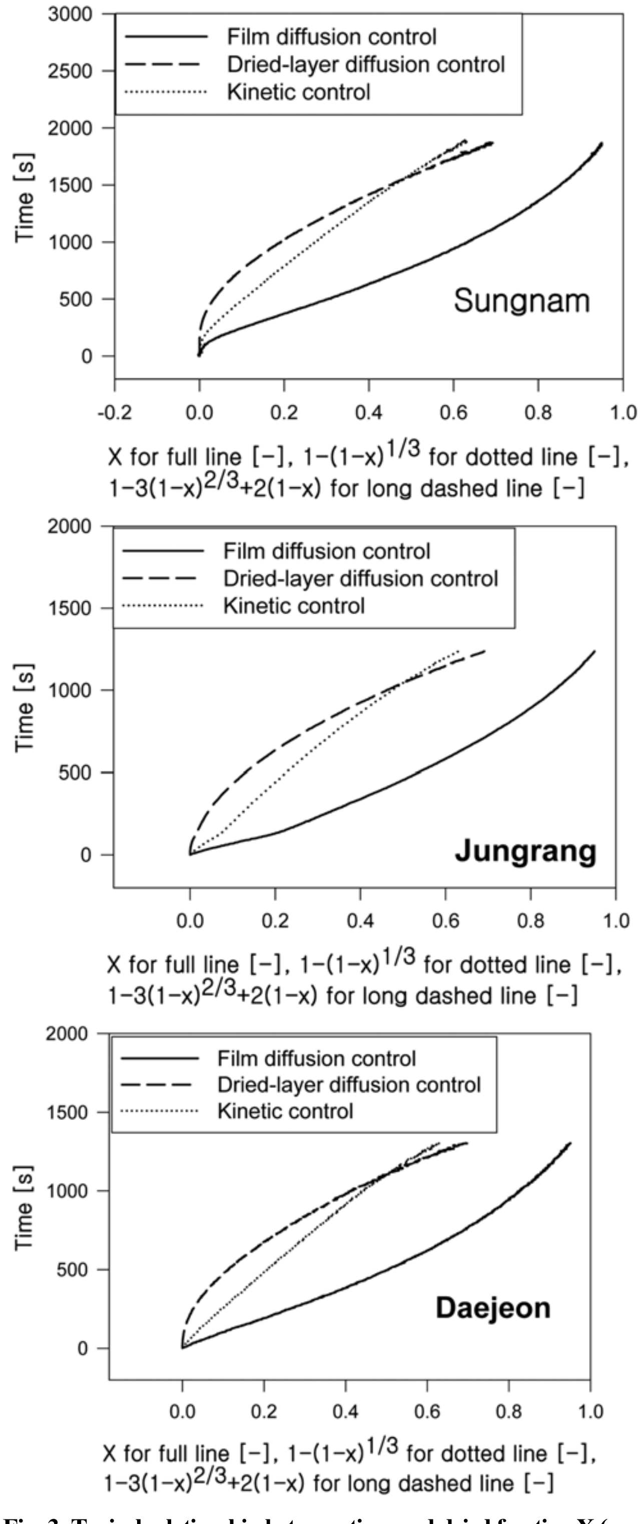

Fig. 3. Typical relationship between time and dried fraction X (m_o= 0.5 g, T=423 K).

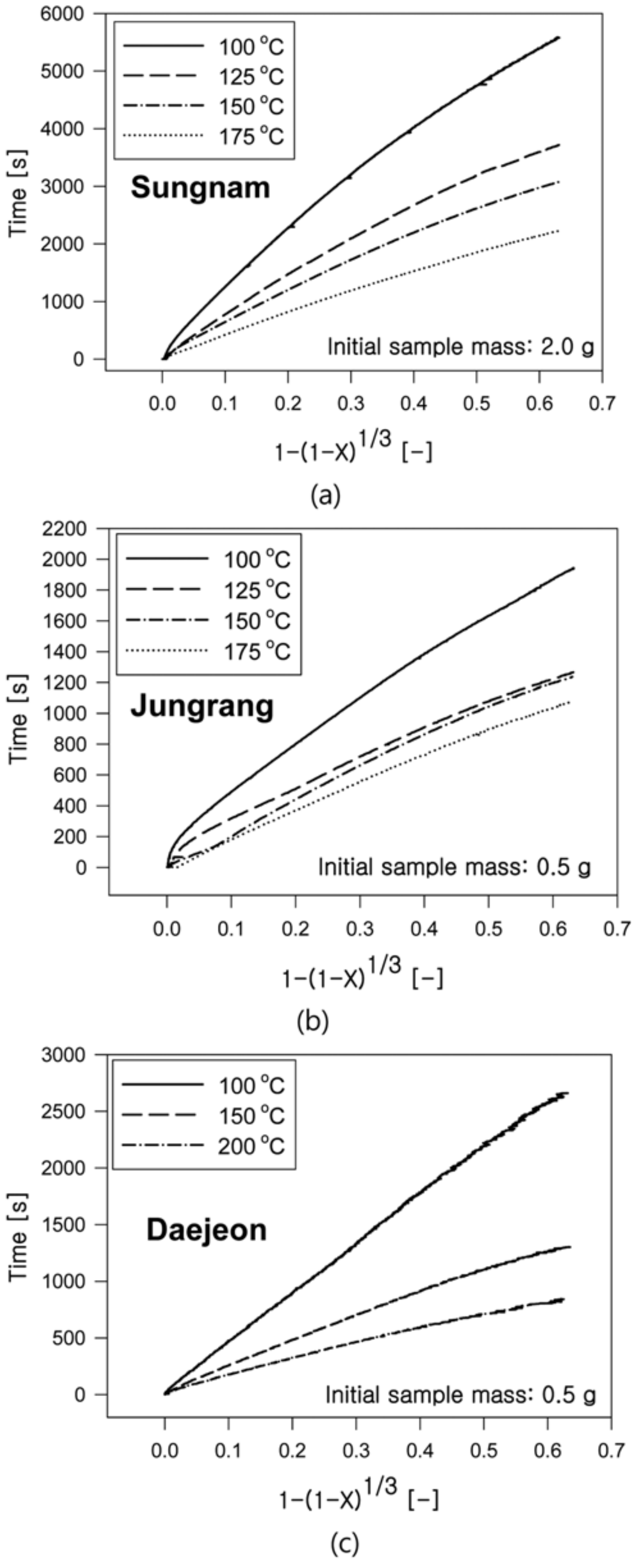

Fig. 4. Typical relationship between the conversion and time at different temperatures.

decreases, the heat transfer rate increases, but the resistance to the diffusion mass transfer of moisture vapor decreases in the dried layer. Therefore, the drying rate increases and then the slope of a plot in Fig. 4 decreases as temperature increases or the initial sample mass

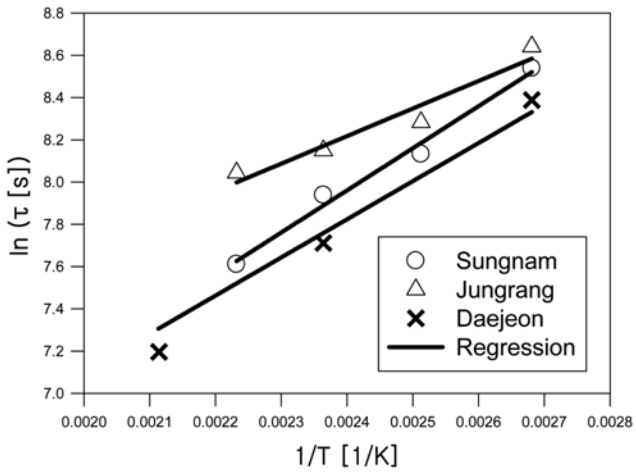

Fig. 5. Typical relationship between complete drying time and temperature (initial sample mass: 0.5 g for Sungnam and Daejeon, 1.5 g for Jungrang).

Table 2. Coefficients for Eq. (5)

Name	a [s/kg^b]	b [-]	E [kJ/g mol]
Daejeon	5303	0.7698	17.64
Sungnam	1223	0.5497	17.14
Jungrang	5361	0.8064	17.11

decreases.

The dried fraction X at a time t was correlated to the initial sample mass and temperature as follows.

$$t = a m_o^b e^{\frac{E}{RT}} \{1-(1-X)^{1/3}\} \quad (5)$$

The coefficients a, b, and activation energy are summarized in Table 2. Therefore, the drying rate was obtained as follows.

$$\frac{dX}{dt} = \frac{3e^{-\frac{E}{RT}}}{a m_o^b}(1-X)^{2/3} \quad (6)$$

The time required for complete drying of a sample depended on the radius of an initial sample sphere by an exponent of 2.309, 1.649, and 2.419, not by the unity shown in Eq. (1b). As a result, Eq. (5) seemed to include some effects of conduction heat transfer and diffusion mass transfer of moisture vapor in dried solid layer on drying rate [15]. But activation energies were found very similar but smaller than that of Jiang et al. [8]. The present activation energies were in the range of the reported values, 2.98 kJ/g mol to 58.9 kJ/g mol [8, 15,20-27].

CONCLUSION

The drying mechanism of sewage sludge was well described by an unreacted core model that considered the zero order on gas reactant concentration and a solid particle of unchanging size. The kinetic rate was found to be the rate-controlling step of the drying mechanism. However, the drying rate seemed to be influenced somewhat by heat and mass transfer rate through the dried solid layer. The mean activation energy of drying rate for sewage sludge was 17.30

kJ/g mol. The drying rate for sewage sludge was expressed by Eq. (6).

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NOMENCLATURE

a : coefficient [s/kg^b]
b : exponent [-]
C_{Bc} : moisture content of gas phase at radius of undried core [kg moisture/m^3]
C_{Bs} : moisture content of gas phase at the particle surface [kg moisture/m^3]
D_e : effective diffusivity of moisture in dried solid layer [m^2/s]
E : activation energy [kJ/kg mol]
m : sample mass at time t [kg]
m_o : initial sample mass [kg]
m_∞ : final sample mass after complete drying [kg]
k_g : film mass transfer coefficient of moisture vapor [m/s]
k_s : drying rate per unit surface area per unit time [kg moisture/m^2 s]
R_p : radius of an initial sample [m]
R : ideal gas constant, 8.314 [kJ/kg mol K]
r_c : radius of undried core [m]
t : time [s]
T : temperature [K]
X : conversion of drying [-]

Greeks

ρ_B : initial water content per unit volume of sample [kg/m^3]
τ : time for complete drying [s]

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