Analysis on the Heat Efficiency of Hot-Air Drying System

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***Abstract*—Conveyor-belt hot-air drying equipment was developed and used in this study to investigate the feasibility of new heat-efficiency-improvement technology. This novel technology reduces the amount of heat generated by the heater in the new hot-air drying furnace. Sludge sample types A and B used in the study were obtained from a city water treatment plant. Samples that had undergone first-stage dehydration were collected frequently during the experimental period. The result from analyzing the total moisture content in the sludge showed that the average total moisture content detected in Type A sludge samples was 35.12% and that in Type B samples was 51.3%. These samples were treated using various temperatures and hot-air supply rates. Evaluation of the drying efficiency of the conveyor-belt hot-air drying system using the Freeman-Carroll method, showed that the drying rate remained constant with temperature and power. Although Type B samples were dried at high temperature, their drying rates were similar to those of Type A samples, which could be dried at lower temperature. This was because of the drying effectiveness of the hot-air as well as the steady temperature inside the dryer equipment.**

Keywords-drye; conveyor; hot-air drying; thermal efficiency; moisture; mass transfer

I. INTRODUCTION

The heat and mass transfers in a hot-air drying system are initiated by moisture and temperature gradients formed by complex phenomena. These phenomena include such as vapor diffusion due to variations in vapor pressure, variations in physical constants, such as the specific heat of the substance to be dried according to its moisture content, heat transfer coefficient and coefficient of diffusivity, volume of water evaporated in the air contact area and energy loss due to vaporization volume, diffusion of water evaporated from the substance to be dried, and convective mass transfer into air. Numerous studies on heat and mass transfer for these drying phenomena have been performed [1-2]. However, most researches on drying have focused only on the importance of the apparatus size, heating type, and operability, as well as on drying analysis to indicate the form of drying in relation to the properties of the substance to be dried. In contrast, little research has been conducted on development of the drying apparatus, or on application of waste-heat-collection technology to increase the efficiency of energy usage [3-5].

Furthermore, drying systems, which could include a heat-based water removal process and mass transfer by dehydration control, are important in both the food processing industry and for sludge management. Drying can extend the storage life of a substance and is effective for reducing storage volume to lower delivery cost [6-7].

In this study, we investigate the feasibility of new technology that could lead to improvement in the thermal efficiency of a hot-air drying furnace by changing the amount of heat generated by its heater.

II. THEORETICAL CONSIDERATION

The energy efficiency of a dryer is determined by the ratio of the energy equivalence of the total cost (including apparatus depreciation related to total energy, i.e., input energy, both heat and electricity) to the sum of the heat (q1) needed to increase the temperature (wet-bulb) of the substance to be dried, the energy used in water evaporation (q2), and the radiation heat loss (q3). However, in this study, the energy efficiency was calculated as the relationship between the sum of the sensible heat required to reach the wet-bulb temperature of the substance to be dried, and the latent heat required for water evaporation, to the total input energy, as given by Eq. 1.

$$n = \frac{q_1 + q_2}{Q} = \frac{t_i - t_o}{t_i - t_a} \qquad \text{..... (1)}$$

n : Thermal efficiency [%]
Q : Hot air generator calories [W]
q : Cost of drying operation calories [W]
h : Heat transfer coefficient [W/m² • K]
t : Hot-air temperature [K]
a : Open air
g : Glass surface to dry
i : Input of the dryer
o : Output of the dryer
p : Hot-air generator
r : Exhaust duct
s : The surface to dry

III. Experimental Appratus And Materials

A. Materials

The Types A and B sludge samples used in this study were obtained from a city water treatment plant, and samples that had undergone 1st-stage dehydration were collected frequently during the experimental period. The result from analyzing the total moisture content in the sludge showed that the average total moisture content detected in sludge Type A samples was 35.12% and that in Type B samples was 51.3%. These samples were treated using various temperatures and hot-air supply rates. The properties and conditions of the experimental sludge types are presented in Table 1. The properties of the samples were analyzed in accordance with the waste pollution ISO standard [8].

TABLE I. CHARACTERISTIC OF SEWAGE SLUDGE SAMPLES USED IN THIS STUDY

Parameter	Type A samples	Type B samples
Moisture contents (%)	35.12	51.3
Hot-air feed rate (m/s)	0.12 - 0.24	
Conveyor belt speed (rpm)	30	
Supply temperature (℃)	100 - 180	

B. Test Equipment

The schematic of the box-type conveyor-belt drying furnace (2150 × 1400 × 1300 cm) to be used in the experiment is shown in Fig. 1. It is divided into four zones (A, B, C, and D), from each of which samples are collected hourly to measure their moisture content. The temperature in each zone is controlled using a steam heat exchange [750 Kw] and the substance to be dried passes in sequence from zone A to D to be dried.

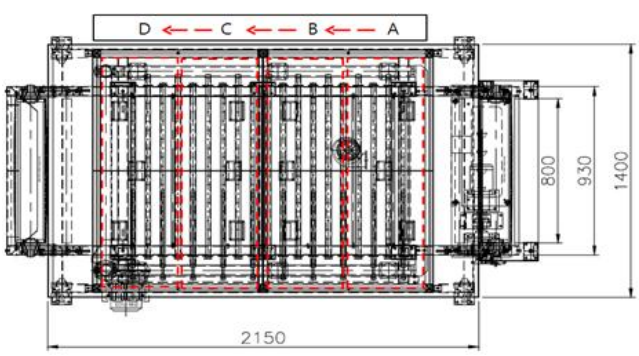


FIGURE I. DRAWING OF THE DRYING FURNACE USED IN THE EXPERIMENTS

Hot air is supplied to each zone from two locations, and an exhaust vent is located at the very front of each zone. One hot-air generator produces hot air at 1.2 m/s, and the all of the exhaust gases from each zone are collected and exhausted to the outside. Fig. 2 shows a photo of the box-type conveyor-belt dry furnace used in this study.

FIGURE II. BOX-TYPE CONVERYOR-BELT DRYER

IV. Result And Discussion

A. Discharge Sludge Concentration Distribution According to Conveyor Belt

In the conveyor belt transfer of a high moisture content sample, the moisture and properties of the sample affect the residence time and moisture content ratio. The residence time allocation of the conveyor belt sample is expressed as E(t) and calculated by Eq. 2 below.

$$E(t) \cong \frac{cj}{\sum_{i=0}^{\infty} cj\Delta t} \qquad \text{.....(2)}$$

cj = The concentration of the initial moisture concentration

When transferring a sample using a conveyor belt, the properties and residence time of the sample become important factors in determining processing efficiency. The result from analysis of the sludge moisture content according to the drying time (using Eq. 2) is shown in Figs. 3 and 4. Type A sludge samples showed a large difference between the concentrations in the early half of the drying process, and in the latter half of the drying process, but Type B samples showed concentrations above a certain level as the drying progressed from the early half toward the latter. This may be due to the fact that moisture was removed in two places, 15 minutes after a certain amount of moisture content started to decrease, as the density of the hot-air contact area of the sludge increases after the water evaporates at 180 ℃ or above. In addition, the sludge at 100 ℃ or less shows low moisture reduction in relation to hot-air contact area. This reduction according to the internal temperature of the dryer had significant effects on moisture transfer from the sample.

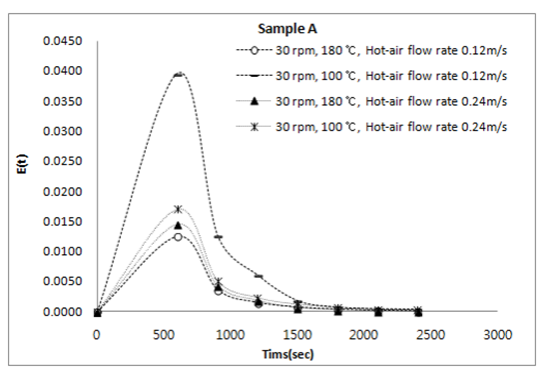


FIGURE III. EXIT AGE DISTRIBUTION OF CONVEYOR BELT

SPEEDDS FOR TYPE A SAMPLES (30 RPM)

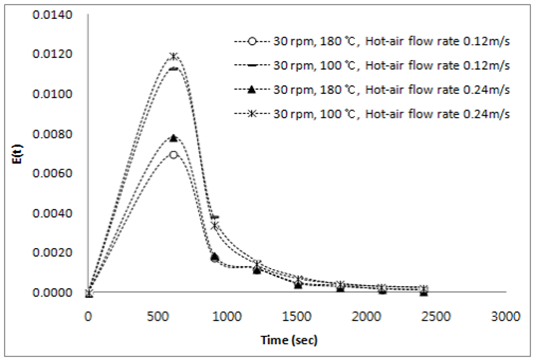


FIGURE IV. EXITAGE DISTRIBUTION OF CONVEYOR BELT SPEEDDS FOR TYPE B SAMPLES (30 RPM)

B. *Drying Reaction Mechanism of the Hot-Air Drying Apparatus*

The temperature condition in the hot-air drying apparatus is one of the operation factors, and was obtained by using a TGA curve, which shows the change in mass when water-containing sludge is heated from 20 ℃ to 180 ℃ at a rate of 4 ℃/min. Using this curve, the rate of thermal decomposition was assumed to have the Arrhenius form of degree n and was calculated by Eq. 3 and 4 below [9-10].

$$\frac{da}{dt} = k(1-a)^n \tag{3}$$

$$\frac{da}{dt} = \mathcal{A}\exp\left(-\frac{\mathrm{E}}{\mathcal{R}\mathrm{T}}\right)(1-a)^n \tag{4}$$

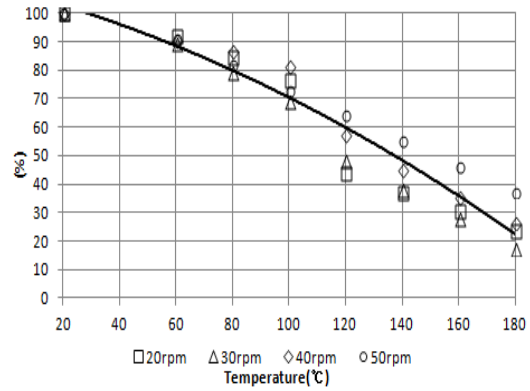
Furthermore, it can be transformed to Eq. 5 below by relating it to the heating rate through the Freeman-Carroll method and taking the log [11-12].

$$\frac{-\frac{\mathcal{R}}{\mathrm{E}}\Delta\ln(\frac{1}{\mathrm{T}})}{\Delta\ln(1-a)} = \frac{\Delta\ln(\frac{da}{dt})}{\Delta\ln(1-a)} \tag{5}$$

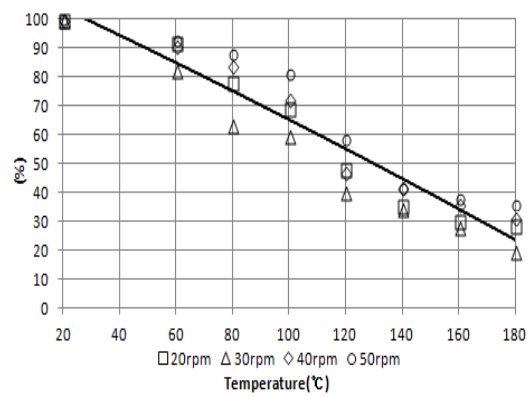
a :	Fraction of material decomposed at time (min^{-1})
t :	Time (min)
E :	Activated energy (kJ/mol)
$\mathcal{R}$:	Rate constant (8,3145J/mol . K)
T :	Absolutely temperature (K)
n :	Order of reaction
$\mathcal{A}$:	Initial concentration (mg/kg)

To evaluate the drying mechanism of the new drier, the hot-air drying constant was calculated using the processing efficiency according to the change in power and temperature at hot-air injection points, and the Freeman-Carroll method was used to investigate the hot-air drying mechanism of the sludge.

Furthermore, the results obtained using the TGA curve, which represent mass variation, and which is used to identify the hot-air drying mechanism, are shown in Fig. 5. Results for Type A samples for different power levels were similar to the measured TGA curve of the conveyor-belt hot-air drying apparatus, and the Type B samples showed higher mass variation than the measured TGA curve of the hot-air drying apparatus, based on the power at the time of hot-air injection. Although this may be due to the moisture content of the sludge, it may also be due to the fact that the Freeman-Carroll method was used for calculations because accurate information on the Arrhenius equation-type hot-air drying mechanism based on the TGA curve was not provided.



(a) Type A samples

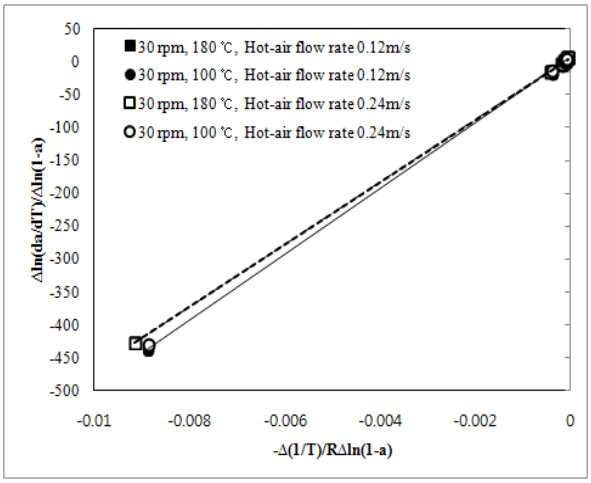


(b) Type B samples

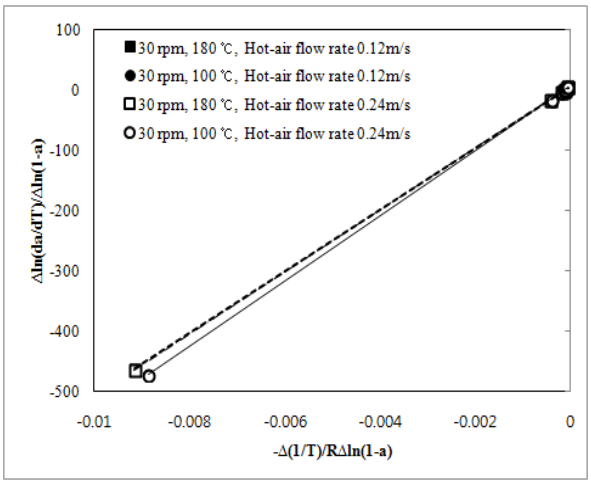
FIGURE V. VARIALTION IN HOT-AIR DRYING ACCORDING TO T.G.A. RESULTS

To measure the hot-air dryer efficiency, the hot-air-drying mechanism was calculated using Eq. 5, which is related to the hot-air flow rate, as shown in Fig. 6.The linear results of sample types A and B that were obtained by inputting the direct test results into Eq. 5. They indicated good operation of the box-type conveyor-belt hot-air apparatus and effective hot-air drying. Liu et al. also reported effective hot-air drying because they also obtained linear results based on the Freeman-Carroll method, and their values were near the lines [13]. Based on the results of Type A (a) and Type B (b) samples in Fig. 6, (a) shows a high hot-air drying rate in the latter half of the drying process as the temperature and power increase; whereas (b) shows a constant hot-air drying rate according to variations in temperature and power. These are judged to be the results of the contribution of moisture content in the Type A samples and to the removal property of the Type B samples. Although the Type B samples showed hot-air drying under conditions requiring high temperature, their hot-air drying rates were similar to those of Type A samples. This indicates effective drying even at temperatures of 100 ℃ or higher. The moisture content at various dry air temperatures for different drying rates declines continually either with

increase in drying time or by reduction of moisture content, as revealed by comparison with the study of Kim et al [14-15].



(a) Type A samples



(b) Type B samples

FIGURE VI. DATA CALCULATED USING FREEMAN-CARROLL METHOD

V. CONCLUSION

Moisture is removed in two places 15 min after a certain amount of moisture content begins to decrease, as the density of the hot-air contact area of the sludge increases after the water evaporates at 180 ℃ or above.

Based on the results of the Freeman-Carroll method, the conveyor-belt hot-air drying apparatus was operated properly to produce satisfactory drying results. Type A samples showed a high hot-air drying rate in the latter half of the drying process as the temperature and power increased; whereas, Type B samples showed a constant hot-air drying rate according to variations in power and temperature.

Although Type B samples showed hot-air drying under conditions requiring high temperature, their hot-air drying rate was similar to those of Type A samples. This shows effective drying even at low temperature, because of the hot-air drying power and stable internal temperature of the apparatus.

The moisture content at various dry air temperatures, for different drying rates, declines continually either with increased drying time or by reduction of moisture content.

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