Korean J. Chem. Eng., **27**(6), 1822-1828 (2010)
DOI: 10.1007/s11814-010-0413-2

A study on air jet drying for water content reduction of sludge

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(*Received 4 March 2010 • accepted 28 August 2010*)

Abstract−An air jet drying system composed of a turbo blower, an air ejector and three stage cyclones is constructed to produce a dried powder through water content reduction of dewatered cake obtained from sludge treatment process. The air flow to be ventilated by the turbo blower forms a high speed flow field by passing through the air ejector and a circulative flow field by passing through the cyclones. Dewatered cake, 100 mm in size, is disintegrated by jet and collision through passing the air ejector and becomes fragmented with size no more than 2 mm. These fragmented particles follow air flow and are dried as moisture is evaporated from particle surface. A powder composed of 1.6 mm spherical particles is produced from pilot scale equipment of 1 ton/hr under the conditions of air velocity, maximum flow rate and air temperature profile of 84 m/sec, 180 m^3/min and 73-28 °C, respectively. The air dried powder with average water content of 49.8 wt% is recovered after drying the dewatered cake with water content of 83.3 wt% in a real operation, indicating 33.5 wt% decrease in water content. It is estimated that the power consumption of the air jet drying system requires 92 kWh/Ton to reduce the water content by 33.5 wt%, which is no more than a half against heat drying system to consume 164 kWh/ton.

Key words: Air Jet Drying, Sludge, Dewatered Cake, Air Dried Powder, Water Content, Particle Size, Energy Consumption

INTRODUCTION

In Korea, up to 1.5 million tons of sludge per year is generated from waterworks or wastewater treatment plants as well as from pulp or iron manufacture processes. Approximately 80% of this sludge is handled by the ways of ocean dumping and landfill. Only 20% is treated by incineration or recycling after reducing the water content by a belt press or filter press dewatering equipment. The higher levels of ocean dumping and landfill are due to the much lower cost and the few technologies available for reducing the water content of sludge. However, these ways have some social and environmental problems. It is anticipated that ocean dumping will be prohibited after 2012 by international ocean environmental regulations. Therefore, the needs for proper management and reuse of sludge have been emphasized. The water content of a dewatered cake produced from belt press or filter press equipment to be used now at the industrial field widely is approximately 80 wt%. When this dewatered cake is incinerated or dried, the energy consumption is very high due to its high water content. On the other hand, the economic cost of further reducing the water content of dewatered cake is also high.

Technologies to reduce the water content of sludge or dewatered cake can be divided into two areas. The first is to reduce the water content by improving the efficiency of dewatering equipment, and the second is to dry the dewatered cake produced from the dewatering equipment. Studies of the former include thermal dewatering and electro-osmotic dewatering technology [1-4]. These technologies are investigated to produce dewatered cake with a water content of 50 wt% by applying heat or an electric force to the sludge. These techniques have some difficulties in commercialization because of high energy consumption as well as problems such as electric corrosion or hot water management. The second area includes heat drying technology by hot wind, rotating disc and rotary kiln system. Some studies have been able to produce a dried powder with <40 wt% water content by allowing direct contact of the dewatered cake to a heat source at 200-600 °C [5-7]. Unfortunately, the cost of the heat drying method is almost double that of ocean dumping. Moreover exhaust gas such as NOx and SOx is generated.

The aim of this study was to develop air jet drying technology with less energy consumption than existing heat drying technology. Air jet drying pilot scale equipment consists of a turbo blower, air ejector, 3-stage cyclone and separator, converting the dewatered cake into an air dried powder through only high speed air and circulation flow. This paper is composed of three parts. The first explains the properties of the equipment by measuring the air velocity, air temperature and air rate. The second examines the drying properties of the dried powder by measuring the particle size distribution and water content. The third reports a feasibility study that compares the results of the present system with the heat drying method using the continuous operation performance data. An air jet dryer with an air velocity, air temperature and flow rate of 84 m/sec, 73 °C and 180 m^3/min, respectively, produces an air dried powder with a water content of 49.8 wt% and a particle size of about 2 mm from a dewatered cake with a water content of 83 wt% and size of 100 mm. In this process, the energy consumption is approximately 92 kWh/ton, which is half that of heat drying. Therefore, this technology is feasible.

1. Air Drying Mechanism

Air drying is carried out in two zones: a high speed flow field

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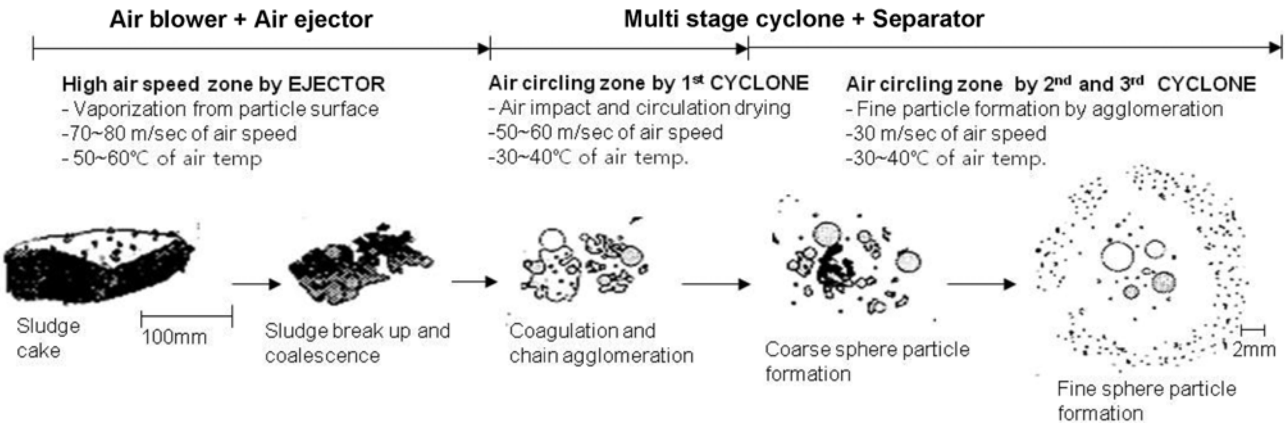


Fig. 1. Powder formation process from dewatered cake in the air jet dryer.

by an air ejector and a circulative flow field by cyclones. The dewatered cake is broken into particles by the jet and collisions between the cakes to the ejector in the high speed flow field, and the disintegrated particles are then dehumidified and dried during transport through the circulation flow in the cyclone. The major factors that determine the air jet drying performance are the size of the disintegrated particles and the evaporation rate from the particle surface. The drying performance improves with decreasing particle size due to the increased surface area to volume ratio.

Fig. 1 illustrates the process where the dewatered cake forms a powder in the air jet dryer. Air ventilated from the turbo blower passes air at 80 m/sec. A dewatered cake, 100 mm in size, that is fed at the front side of the air ejector is broken into a powder with a particle size <2 mm by high speed air and collisions between particles. These disintegrated particles follow the air flow into the 1st cyclone with a flux and aerial temperature of 50-60 m/sec and 30-40 °C, respectively. The disintegrated particles are converted into a spherical shape under the influence of aggregation and coagulation by interactive process between particles at the circulation zone. The particle size will decrease as the particles flow through the 2nd and 3rd cyclone. The air drying performance will be increased with decreasing particle size. The air drying performance also improves the longer the particle remains in the cyclone (i.e., increased residence time). Therefore, it is important to design a cyclone with different L/H (L: Length of cyclone, H: Height of cyclone) ratios.

The particle size can be different according to the components in the sludge. Typically, the particle size generated from inorganic sludge is smaller than organic sludge due to the superiority of the disintegrated properties, which improves the drying performance during the air drying process. It is possible to produce dried powders containing the proper water content and size if the air flow conditions, such as the air velocity, flow rate and air temperature can be controlled properly.

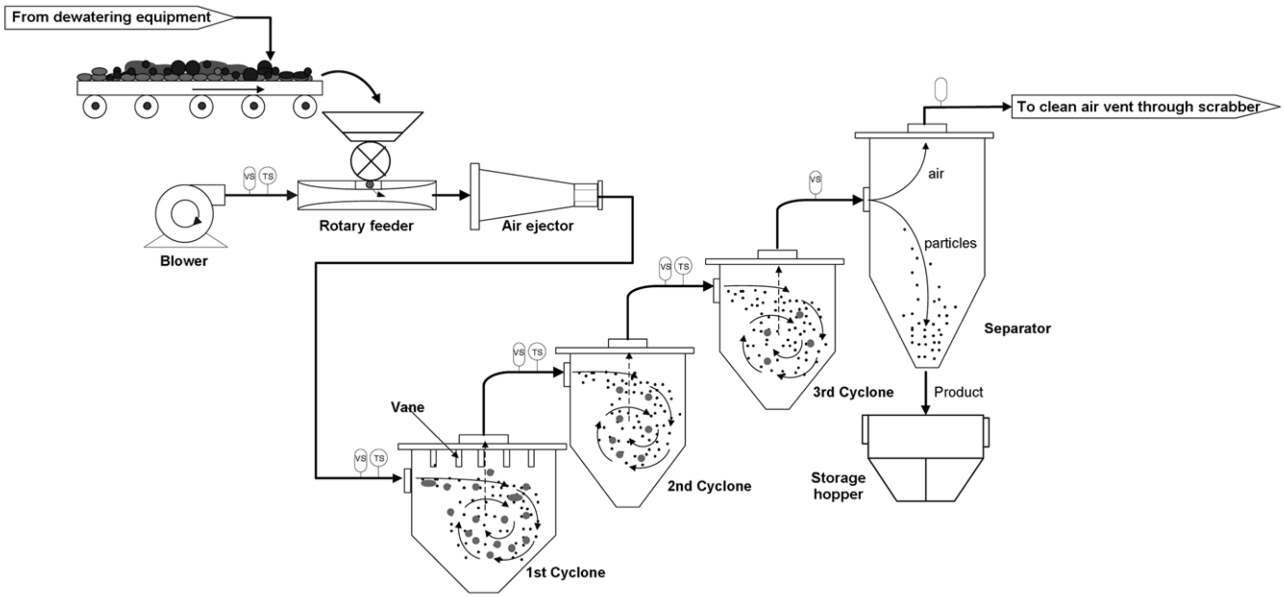
EXPERIMENTAL METHODS

1. Experimental Apparatus

As shown in Fig. 2, the air jet drying equipment to reduce the water content of a dewatered cake produced from belt press dewatering equipment is composed of a turbo blower, sludge feeding unit, air ejector, multi cyclone, separator and scrubber. Fig. 2(a) shows a schematic diagram of air jet drying system and Fig. 2(b) gives a photograph. Table 1 lists the design factors and operating variables of the equipment and sludge properties used in this study. The air velocity, flow rate and pressure to be ventilated from the turbo blower are <80 m/sec, 150-180 m^3/min and 0.5 bar, respectively. The rotary feeder is a unit to supply a dewatered cake at a constant ratio of 1 ton/hr at the front side of the air ejector. The cyclone is composed of three stages, and the L/H ratio of each stage is different. The property of each cyclone is determined by the L/H ratio, which means that the particle retention time decreases with increasing of L/H ratio of cyclone. Therefore, the L/H ratio of each stage is designed to be 700/1700, 600/1600, 500/1500 in order to increase the residence time of the particles. The separator with an L/H ratio of 915/3488 to achieve the maximum separation efficiency separates the dried powder and humid air. The separated powder is collected at the storage hopper of low parts, and the water content and size are measured. The humid air is discharged to the atmosphere after the dust is removed at the scrubber.

2. Operating Process of Air Jet Drying System

Fig. 3 shows the operating process of the air drying system. Dewatered cake with a water content of 80-85 wt% is supplied at a constant rate of 1 ton/hr through the rotary feeder. This dewatered cake flows along with air to have velocity, flow rate, temperature and pressure of 80 m/sec, 150-180 m^3/min, 80 °C and 0.5 bar, respectively, at the air ejector. The dewatered cake may also be disintegrated into smaller fragments by the mechanical force of the jet and collisions between particles passing through the ejector, bound water or interfacial water is evaporated from a part of the fragment particles [8]. These fragmented particles pass through the air ejector and transportation tube flow into the cyclone connected in series. The vane in upper inside of the 1st cyclone causes collisions between particles. The circulating particles move downward with the vortex fluid and centrifugal force in the cyclone, and the flowing particles move upward as a result of reverse vortex flow. This is transported into the next cyclone and dried while flowing with the rising air stream generated at the center of circulation flow. Constant drying is performed at the 2nd and 3rd cyclone through this process. The air dried powder and humid air to pass the multi-cyclone are separated at the separator. The air dried powder is collected at the lower



(a)

(b)

Fig. 2. Schematic diagram of air jet drying system (a) and photograph (b).

Table 1. Experimental conditions of air jet dryer

Parameters		Values
Design factors	Capacity of system	10 ton/day
	L/H of 1st cyclone	700/1700
	L/H of 2nd cyclone	600/1600
	L/H of 3rd cyclone	500/1500
	L/H of separator	915/3488
	Wet scrubber capacity	120 CMM
Operating variables	Air velocity profile after air jet	30-80 m/sec
	Air flow rate range	150-180 m^3/min
	Air temperature after air jet	85 °C
	Rotary feeding rate	1.0 ton/hr
	Particle retention time	6 min/cycle
Sludge properties	Initial water content	80-85 wt%
	Organic content	55.5 wt%
	Cake temperature	10 °C

side of the separator, and humid air is exhausted into the atmosphere after cleaning up the humid air flow from the upper side of the separator at the scrubber. The time after supplying the dewatered cake at the front of air ejector until the powder is recovered at the separator, which is called the residence time, was approximately 6 min. The dewatered cake changes into an air dried powder after the following three stage process: (1) fragmented particles are formed by the jet and collisions at the high speed flow field zone; (2) these particles are dried by flowing downward and upward in the cyclone; and (3) the final yield is determined after separating the air dried powder and humid air at the separator. The drying performance of this equipment depends on the operation conditions of each unit as well as the water content and components of the sludge materials.

3. Analysis Methods

The air velocity, flow rate and temperature profile are measured at the rear side of the turbo blower, air ejector, 1st cyclone, between the 1st and 2nd cyclone, and between the 2nd and 3rd cyclone. The air velocity and temperature are measured at each point as the dewa-

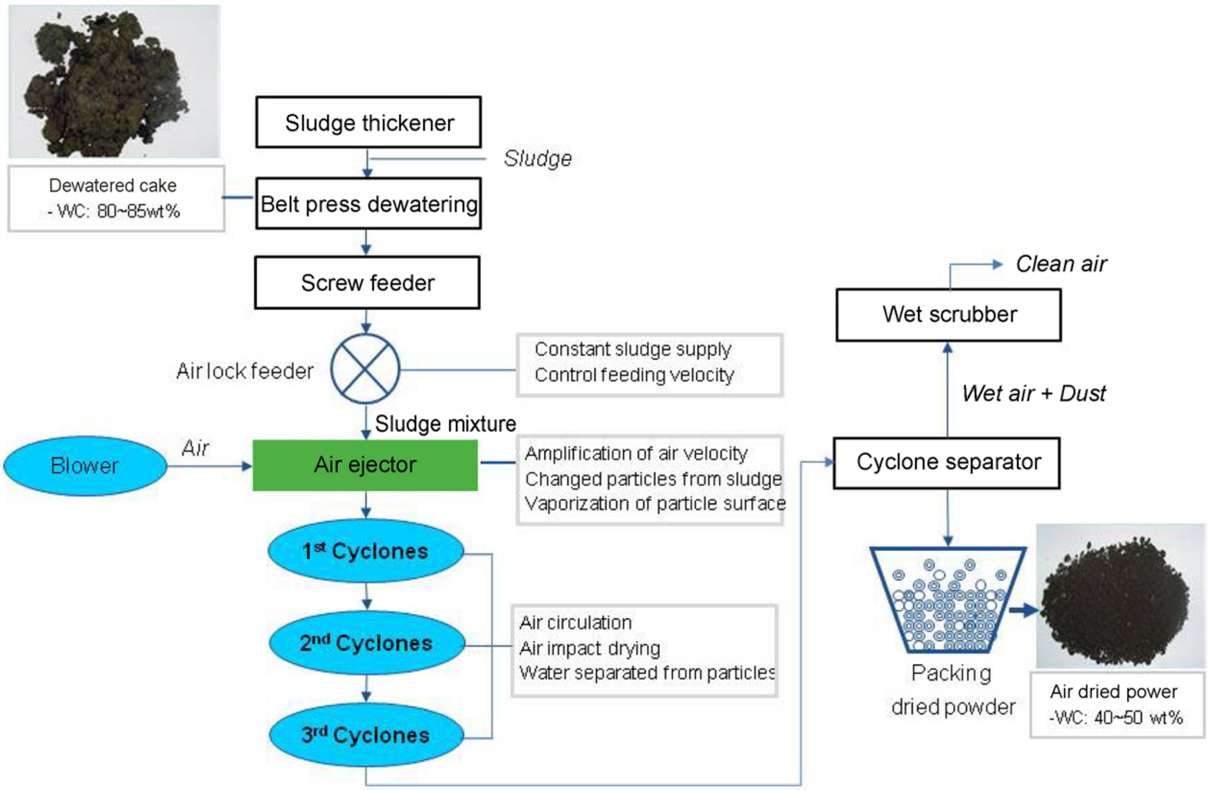


Fig. 3. Operating process of the air drying system.

tered cake is supplied with a constant ratio after stabilizing the air flow condition through idle operation for approximately 15 minutes. The water content of the dried powder is also measured as the air flow rate and quantity of dewatered cake, by which the drying ability of the air jet drying system is determined. The water content of the dried powder and dewatered cake is obtained using a gravimetric method, which involves measuring the weight difference before and after drying the samples at 105 °C for one hour. The size distribution of the dried powder is a major factor to identify the drying properties and efficiency of the air jet drying system. This is obtained using a sieving method which classifies the sample of the dried powder. Two hundred grams of the dried powder is classified into five grades, and the weight and water content of the powder are measured at each grade. The mean size and water content are obtained from the data.

RESULTS

1. Temperature Profile and Air Velocity of Air Jet Dryer

Fig. 4 shows the air velocity on the measurements at the air ejector and each cyclone. The air velocity plays an important role in breaking up the dewatered cake, as shown in Fig. 1. The dewatered cake is disintegrated finely due to the high air velocity, which can make smaller particles resulting in a faster drying rate. This air velocity profile was measured at the each point of the equipment in the case of an air flow rate of 180 m^3/min. The air flow rate is controlled from 150 to 180 m^3/min using a turbo blower. The air velocity profile from the turbo blower to the rear side of the air ejector is 70-85 m/sec. This zone is a high speed flow field, where the

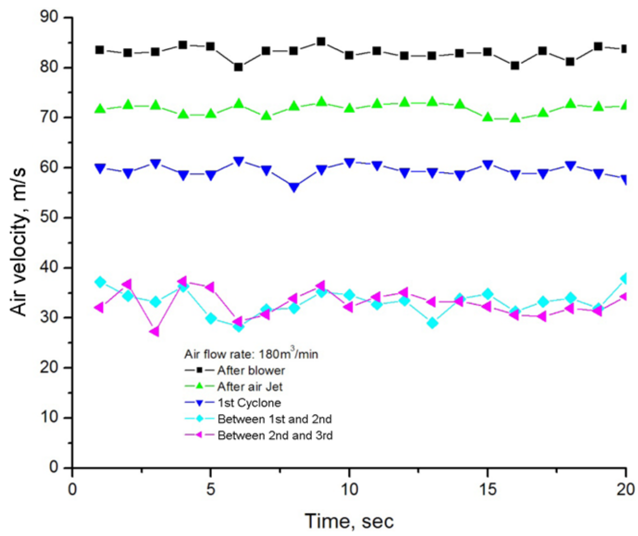


Fig. 4. Air velocity profile to be measured at the air ejector and each cyclone.

supplied dewatered cake is disintegrated. The air velocity increases with decreasing air ejector diameter, but this system is designed to obtain a proper speed considering the power consumption. The circulative flow field is formed from the ejector rear to the 3rd cyclone. The velocity profile is 30-60 m/sec at this zone. The flow velocity is approximately 60 m/sec at the 1st cyclone and 30-40 m/sec at the 2nd and 3rd cyclones. The particles disintegrate well when the air velocity is fast, resulting in the production of small particles and good

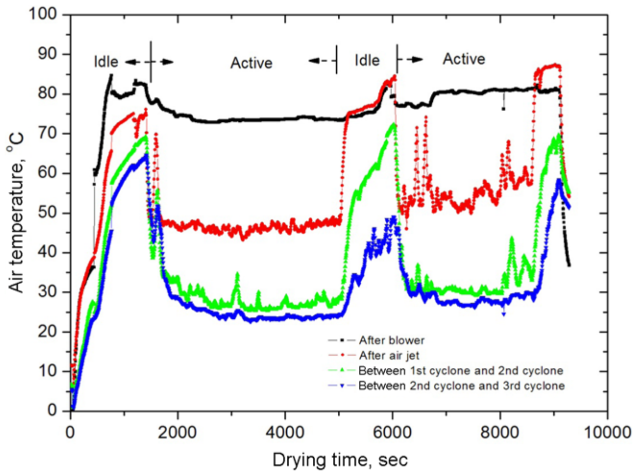


Fig. 5. Air temperature change at each point of the equipment during operation.

evaporation of water from the particle surface. This high flow rate can evaporate a large quantity of water because the flow rate plays a role in containing the water to be evaporated from the particle surface.

The air temperature increases as a result of friction between the air and fan of the blower when air is ventilated from the turbo blower. It means that there is no requirement for air preheating equipment. Fig. 5 shows the temperature change at each point of the equipment during operation and Table 2 lists the average temperature. The initial air temperature of 6.5 °C increased to 85 °C as a result of friction between the air and fan while being ventilated from the turbo blower. The temperature profile of each point is maintained uniformly on idle operation so as not to supply dewatered cake and decreased rapidly on the active operation to supply it. The range of the temperature decline is identified by 25 °C, 36 °C and 35 °C at the air ejector, between the 1^{st} and 2^{nd} cyclone and between the 2^{nd} and 3^{rd} cyclone, respectively. The decrease in temperature to 25-36 °C during the operation is attributed to the moisture evaporated from the particle surface. The factors affecting the air drying performance are the air flow rate, velocity and temperature. The air flow rate and velocity are determined by the design factors of equipment, and the air temperature is affected on the dewatered cake and room temperature.

2. Size Distribution and Water Content of Air Dried Powder

The particle size of the dried powder is a major factor for estimating the performance of air drying equipment. Table 3 lists the size distribution and mass median diameter (MMD) of dried powder obtained after classifying the particles into five grades by sieving. The median diameter of each grade is 2.4, 1.5, 0.75, 0.4 and 0.25 mm and the respective mass measured at each grade is 70.45, 90.21, 32.14, 4.84, 0.59 g. According to Eq. (1), the mass median diameter (dmm) is determined by multiplying each mass (m_i) by each median diameter (dm_i) divided by the total mass (M) gives [9].

$$dmm=\sum\{(m_i \times dm_i)/M\} \quad (1)$$

The mass median diameter of the dried powder of the waterworks sludge obtained using this method is 1.66 mm. This size is relatively small considering that the air dried powder produced from wastewater sludge is approximately 2.0 mm. In addition, 64% of the particles are <1.5 mm, which means that the amount of fine particles is much more than coarse particles. Also, the degree of disintegrated particle is superior and evaporation from the particle surface is well done. The reason that the size of dried powder of the waterworks sludge used in this study is relatively fine is attributed to the higher inorganic and SiO_2 content than wastewater sludge [10,11]. The inorganic and SiO_2 content improve disintegrated degree because these materials weaken the cohesion between particles, which has sludge make a fine particle. Fine particle in the air fluid results in a higher water evaporation rate from the particle surface.

Table 4 and Fig. 6 show the relationship between the powder size and water content. The water content of fine particles (0.2-1 mm) ranges from 40 to 48 wt%, whereas the water content of the coarse particles (1.0-2.8 mm) ranges from 53.7 to 62.5 wt%. The average water content is 50.1 wt% based on this data. The water content decreased with decreasing particle size due to the higher surface area to volume ratio. So, these two items must be taken into consideration for this design. The first is to improve the disintegrated

Table 3. Particle size distribution and mass median diameter (MMD) of dried powder obtained after classifying the particles into 5 grades by sieving

Median diameter (mm), dm_i	Mass (g), m_i	dmm_i (mm)	dmm (mm)
2.4	70.45	0.85	1.66
1.5	90.21	0.68	
0.75	32.14	0.12	
0.4	4.84	0.01	
0.25	0.59	0.000074	

Note: $dmm=\sum\{(m_i \times dm_i)/M\}$, $dmm_i=m_i \times dm_i$, MMD: Mass Median Diameter, Total Mass (M): 200 g

Table 4. Water content difference as size distribution of air dried powder

Size range (mm)	Mass (g)	Mass fraction	Water content (wt%)
2.0-2.8	70.45	0.36	62.5
1.0-2.0	90.21	0.46	53.7
0.5-1.0	32.14	0.16	48.6
0.3-0.5	4.84	0.02	45.7
0.2-0.3	0.59	0.003	40.1

Table 2. Average temperature of air jet dryer on the idle and actual operation

Items		Room temperature	After blower	After air jet	1^{st}-2^{nd} Cyclone	2^{nd}-3^{rd} Cyclone
Average temperature (°C)	Idle operation	6.5	85	73	68	63
	Actual operation	6.5	73	48	32	28

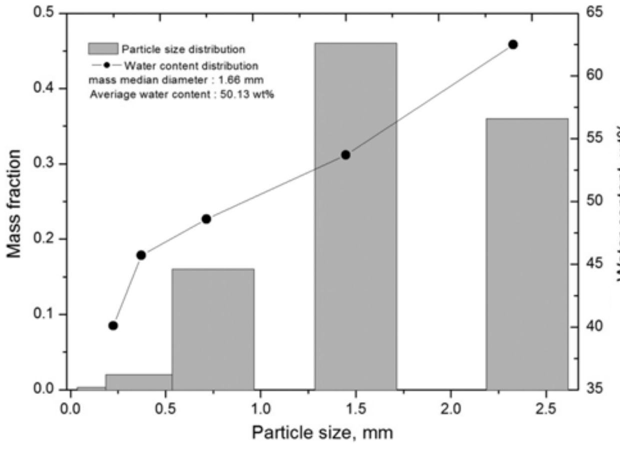


Fig. 6. Relationship with between the dried powder size and water content.

ability of the dewatered cake by increasing the air velocity. The second is SiO_2 content within the sludge. There are some difficulties to use by reusable matter such as compost and aggregate in the case of a fine powder, <1 mm in size, because of the difficulties in storage and transfer. However, coarse powder, >1 mm in size, can be reused due to the easy management. It is essential to determine the design factors to produce the particles with the appropriate size because coarse particles have high water content and fine particles have low water content.

3. Size Distribution and Water Content of Air Dried Powder

Air drying performance and economic efficiency would be estimated on the basis of data obtained from real operation in this chapter. Fig. 7 presents the difference in water content of the air dried powder according to the change in supply rate of the dewatered cake and air flow rate. The water content increases with increasing the supply rate of dewatered cake and with decreasing air flow rate. Therefore, an increase in the supply of dewatered cake means that the amount of the sludge drying treatment increases finally. An increase in the air flow rate means an increase in energy consumption of the

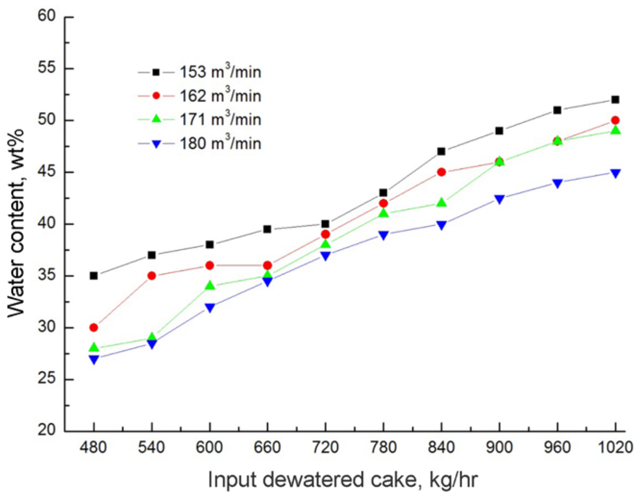


Fig. 7. Difference in water content of the air dried powder according to the change in supply rate of the dewatered cake and air flow rate.

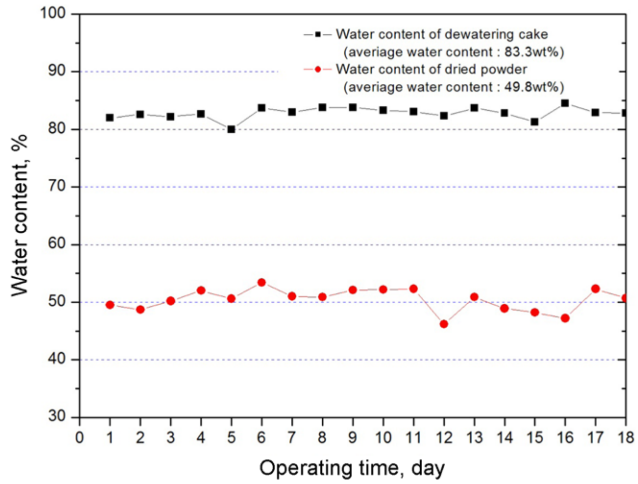


Fig. 8. Water content reduction of dried powder on actual operation.

system. The air dried powder produced from the air drying system is reused by the light aggregate, compost etc. When using reusable matter, it is important to produce an air dried powder with water content <50 wt%. For this, it is essential that the air flow rate of the rear side of the turbo blower and air velocity be 180 m^3/min and 84 m/sec respectively, as shown Fig. 7.

Fig. 8 presents the results to operate continuously during 18 days. As shown in the figure, air dried powder with an average water content of 49.8 wt% was recovered after drying dewatered cake with a water content of 83.3wt%, indicating a 33.5 wt% water reduction. Table 5 compares the energy consumption required for this level of water reduction by heat drying with that by air drying. With heat drying, the total consumption energy is required by 169 kWh/ton to achieve an air dried powder with water content of 49.8 wt%: of this total energy, 116 kWh/ton and 53 kWh/ton was required to heat air by 200 °C and operate the heat drying system, respectively. On the other hand, the air jet drying system does not require energy to heat the air and an operation power of only 92 kWh/ton is required to drive the turbo blower. Therefore, energy consumption for the driving air jet drying system is approximately a half that of the heat drying system. In addition, useful bacteria such as actinobacteria in the powder can be kept viable after drying because the air jet drying system does not supply a high temperature heat source. Therefore, this air dried powder can be reused as compost materials.

Table 5. The comparison of energy consumption with heat and air drying

Items		Heat drying	Air drying
Condition	Water content reduction: 83.3 wt%−49.8 wt%=33.5 wt% Efficiency of heat dryer: 60%		
Energy consumption (kWh/ton)	Fuel	116[1]	0
	Electric	53	92
	Total	169	92

Note: (1) 1,000 kg/ton×(0.833−0.498)×540 kcal/kg×0.6=108,540 kcal/ton=116 kWh/ton

CONCLUSION

An air jet drying system composed of a turbo blower, air ejector and three stage cyclones is built to reduce the water content of dewatered cake produced from a sludge treatment process. The air flow is ventilated by a turbo blower and formed a high speed flow field through the air ejector and a circulative flow field through the cyclones. The dewatered cake is disintegrated by high speed flow field and dried by evaporation from the particle surface in the circulative flow field. The mass median diameter (MMD) and water content of the air dried powder are investigated as 1.6 mm and approximately 50 wt% under the condition of air velocity of 84m/sec, maximum flow rate of 180m^3/min and air temperature profile of 73-28 °C. The dried powder with water content of 49.8 wt% produced from drying the dewatered cake with water content of 83.3 wt% at the real operation, which means the water reduction is 33.5 wt%.

It turned out that the energy consumption of the air jet drying system is approximately an half in comparison with that of heat.

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