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Original Article

Energy Efficiency of Fluidized Bed Drying for Wood Particles[1]

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ABSTRACT

This study evaluates the economic feasibility of industrializing fluidized bed dryer for wood particles. The theoretically required heat energy and energy efficiency were evaluated using a pilot scale fluidized bed dryer. When Mongolian Oak wood particles with 50% initial moisture content were dried in the fluidized bed dryer with air of 70℃ air circulating at 1.1-1.3 m/s for 30 minutes, the total theoretically required heat energy was 2,177 kJ. Of this, 1,763 kJ (approximately 81.0%) was used to heat the air flowing in from outside the dryer and 386 kJ (approximately 17.7%) was used to heat and remove water from the wood particles. Actual energy consumed was 7,560 kJ, giving energy efficiency of 28.8%. Thus, to industrialize a drying method such as fluidized bed drying, where the dryer volume is significantly larger than the volume of wood particles, it is necessary to minimize energy loss and maximize energy efficiency by designing the dryer size considering the amount of wood particles and choosing a suitable air circulation rate.

Keywords : wood particle drying, fluidized bed drying, required heat energy, energy efficiency

1. INTRODUCTION

All countries of the world are trying to develop alternative energy options to address energy problems such as resource depletion due to excessive consumption of fossil fuel and limiting greenhouse gas emission, such as CO_2, to minimize global climate change. Lignocellulosic biomass is considered a good candidate alternative energy source to fossil fuels because it is the most abundant energy source on the Earth and a sustainable, carbon neutral and ecologically friendly resource. Lignocellulosic biomass is mainly composed of cellulose (40-60%), hemicellulose (20-40%), and lignin (10-25%). However, there are limits to its use as an energy resource because its composition is interconnected. To increase yield and efficiency

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of production various physical or chemical pretreatments are performed. In particular, because the large quantity of water bonded with the hydrophilic functional group decreases the pretreatment yield, it is necessary to remove the water from the lignocellulosic biomass.

Wood particles are a widely used lignocellulosic biomass in Korea and are usually pretreated physically or chemically after air drying (Jang *et al.*, 2015, Ryu *et al.*, 2016). However, air drying is a very slow process and wood particles can start to decay (Jung, 1990; Kang and Kim, 2004). Therefore artificial drying method is necessary to allow lignocellulosic biomass industrialization. The amount of energy consumed in drying process is approximately 50-70% of total energy consumption in wood process (Jung, 1991). Therefore, some studies about where is the energy used to or how much energy is used have been investigated (Helwa *et al.*, 2004; McCurdy, 2007; Perré *et al.*, 2007).

This study evaluates the theoretically required heat energy and energy efficiency using a pilot scale fluidized bed dryer to evaluate the economic feasibility of domestic industrialization of a fluidized bed dryer, a typical dryer for wood particles.

2. MATERIALS and METHODS

2.1. Specimen

Small diameter less than 150 mm Mongolian Oak (*Quercus mongolica*) from afforestation in Gwanak arboretum (Anyang, Gyenggi-do) was used in this study.

After crushing the log using crushing machine (PRCS-3300ED, Poong Rim Environment Machinery Co., Euiwang), the crushed pieces were milled into wood particles less than 0.5 mm maximum dimension using milling machine (Cutting Mill pulverisette 15, FRITSCH GmbH, Germany), and all fine wood particles less than 0.3 mm were removed by sieving to prevent fire.

2.2. Fluidized bed drying for wood particles

The 0.3-0.5 mm wood particles were dried using the fluidized bed dryer shown in Fig. 1. The dryer is composed of a drying tower, where the wood particles are actually dried; cyclone to recover dried wood particles; fan to circulate air in the dryer; heater to heat the air in the dryer; and condenser to remove the water from the humid air after drying.

When the fan operates, the air in the dryer circulates. The circulation rate can be set to 8 levels between 0.1-0.3 m/s and 1.1-1.3 m/s. The air is heated before flowing into the drying tower. The target drying temperature was 70℃. 400 g of green wood particles were prepared by uniformly mixing 200 g of oven dried wood particles and 200 g of water. The wood particles were input to the drying tower, and they started to dry, floated by the rising current of air heated to 70℃. Heavy wood particles, containing a lot of water, circulated in the drying tower, as they were not able to rise to the

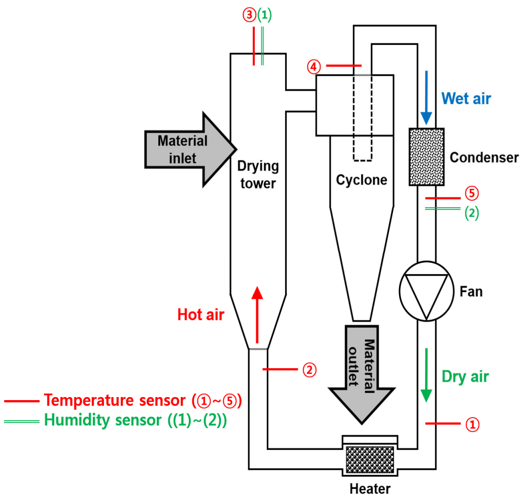

Fig. 1. Fluidized bed dryer for wood particles.

height of the pipe connected to the cyclone. On the other hand, dried wood particles were light enough to reach the cyclone pipe and were then transported to the cyclone and recovered. Thus, only wood particles dried below certain moisture content can be taken to the cyclone. The threshold moisture content is determined by particle size, air rate, drying temperature, etc. The drying conditions used throughout this study were air temperature 70℃, rate 1.1-1.3 m/s, and heater and fan operation time 30 minutes. The target moisture content was 5%. Wood particles taken to the cyclone were collected at the bottom along to the cyclone wall. The air passed through the wood particles from the bottom and exited through the cyclone. Water contained in the humid air from the cyclone was removed in the condenser and dry air recirculated through the dryer.

Five temperature sensors and two humidity sensors were installed in the dryer (Figure 1). When drying the wood particles, the temperature of air surrounding the dryer was 10℃ and relative humidity was 27%.

2.3. Theoretical required heat energy

The total heat energy required for drying wood particles can be classified into five heat energy types, as shown in Table 1, along with the calculation methods and symbol definitions and constants.

H_1 is the heat energy required to heat only wood substance. It can be calculated from the wood particle oven dried weight, specific heat, and difference between initial and final temperatures.

H_2 is the heat energy required to remove bound water connected with the wood cell. It can be calculated from the wood particle oven dried weight, final moisture content, and the heat of desorption per unit mass (H_{de}). The heat of desorption per unit mass is the accumulated value of heat of desorption from fiber saturation point to final moisture content. It can be calculated from the final moisture content of the wood particles and the regression equation, $10^{1.2335-5.408m_R}$ (Jung *et al.*, 2008).

H_3 is the heat energy required to heat the residual water in wood particles after drying. It can be calculated from the wood particle oven dried weight, final moisture content, difference between initial and final temperatures, and the specific heat of water.

H_4 is the heat energy required to heat and evaporate bound water which was disconnected

Table 1. Heat energy required in drying wood particles and calculation method (Jung *et al*., 2008)

Heat energy classification			Formula
$\mathbf{H_1}$		Heat energy required to increase temperature of the wood particles	$W_0 c_w (T_1 - T_0)$
$\mathbf{H_2}$		Heat energy required to overcome the adsorptive power of the bound water	$W_0 H_{de}$
$\mathbf{H_3}$		Heat energy required to heat the residual water in wood	$W_0 m_R (T_1 - T_0) \times 4.187$
$\mathbf{H_4}$		Heat energy required to heat and evaporate the water that is eliminated from the wood	$W_0 \Delta mc (\Delta T + h_{water})$
$\mathbf{H_5}$	$\mathbf{H_{5a}}$	Heat energy required to heat the air flowing in from outside the dryer	$W_0 c_{pa} \frac{\Delta mc \Delta T}{dG}$
	$\mathbf{H_{5s}}$	Heat energy required to heat the steam flowing in from outside the dryer	$W_0 c_{ps} G_0 \frac{\Delta mc \Delta T}{dG}$

W_0 = oven dry weight of wood particles (g), c_w = specific heat of wood particles (1.306 J/g℃)
T_1 = final temperature of wood particles (℃), T_0 = initial temperature of wood particles (℃),
H_{de} = heat of desorption per unit mass of wood particles ($10^{1.2335 - 5.408 m_R}$, J/g_{wood}),
m_R = final moisture content of wood particles (fraction), h_{water} = latent heat of vaporization of water (J/g_{wood}),
Δmc = difference between initial moisture content and final moisture content of wood particles (fraction),
c_{pa} = specific heat of dry air (1.005 J/g℃), c_{ps} = specific heat of steam (1.884 J/g℃),
G_0 = specific humidity of the air flowing in from outside the dryer (g_{steam}/g_{air}),
dG = mass of steam per unit mass of dry air flowing in from outside the dryer can be received (G (specific humidity of air in the dryer) - G_0, g_{steam}/g_{air})

with the wood cell or free water. It can be calculated from the wood particle oven dried weight, difference between initial and final moisture contents, difference between initial and final temperatures, and the latent heat of vaporization of water (h_{water}, J/g_{wood}). The latent heat of vaporization of water is the heat energy required when liquid water is vaporized to steam, and may be calculated using the temperature of outside air (T_a, ℃), 598.25 - 0.6 × T_a (Jung *et al*., 2008).

The heat energy required to heat the air and steam flowing in from outside the dryer can be calculated separately using the oven dried weight of wood particles, specific heat of air and steam, specific humidity of the air flowing in from outside of the dryer, and specific humidity of air in the dryer.

2.4. Energy loss and efficiency

When drying wood particles, aside from the required heat energy considered in Section 2.3, some energy is also lost via diverse routes, such as heating the dryer wall, maintaining the temperature, or heating the air excessively flowing into the dryer. Energy lost in these ways can be minimized by designing a suitably insulated dryer and controlling drying conditions. Energy loss is difference between the actual consumed energy and the sum of the theoretical required heat energies, and energy efficiency is the ratio the total theoretical required heat energy to the actual consumed energy.

$$E\ (\%) = \frac{\textit{Total theoretical required heat energies}}{\textit{Actual consumed energy}} \times 100$$

3. RESULTS and DISCUSSION

3.1. Fluidized bed drying for wood particles

Wood particles were dried in the pilot scale fluidized bed dryer under the conditions: 200 g (oven dried weight), initial moisture content 50%, 70℃ air circulating at 1.1-1.3 m/s for 30 minutes. Wood particles that were transported to the cyclone were recovered: 170.74 g oven dried weight (85.37%), moisture content 5.15%. Wood particles that were not transported to the cyclone, i.e., remained in the drying tower, were also collected: 24.63 g (12.32%), moisture content 1.34%. Wood particles remaining in the drying tower were clumped (see Fig. 2). Surface tension from excess water during early drying caused some wood particles to clump, some were not subsequently separated to enter the cyclone transport pipe, and consequently were exposed to 70℃ air for a relatively long time. Hence, their moisture content was lower than that of wood particles recovered at cyclone. To enhance drying yield and efficiency, an additional action is required, such lightly vibrating the bottom of the drying tower to break up clumps early in the drying process.

Approximately 4.63 g (oven dried weight) of wood particles (2.31%) was lost when recovering wood particles from cyclone and drying tower after drying.

3.2. Theoretical required heat energy

The theoretical required heat energies were calculated only for the 170.74 g of recovered wood particles, since the other wood particles could not be recovered, the required energies for these were considered to energy loss. Therefore, using the equations and constants from Table 1, the various heat energies were calculated as shown in Table 2.

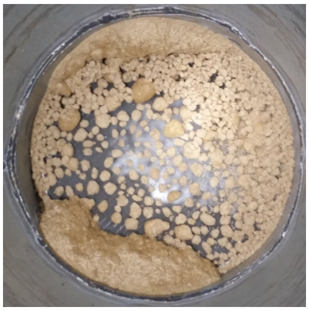

Fig. 2. Clumped wood particles at the bottom of the drying tower.

Total theoretical required heat energies was approximately 2,177 kJ, of which approximately 81.0% was used to heat the air flowing into the dryer and only approximately 17.7% was used to heat and evaporate water in the wood particles. In contrast, when kiln drying lumber or round timber, most heat energy was used to heat and remove water in the wood (77.15%) and only approximately 6.84% of heat energy was used to heat the air flowing into the dryer (Park, 2016). However, unlike kiln drying wood, the internal space of the fluidized bed dryer is large compared to the amount of wood dried, and the amount of the air circulating is also large. Thus, because much more air must be heated, fourfold heat energy was required. Therefore, to decrease energy consumption when drying wood particles, the dryer size

Table 2. Calculated theoretical heat energy required to dry wood particles

		Heat energy classification	Calculation	Ratio
H_1		Heat energy required to increase temperature of the wood particles	13,379 J	0.6%
H_2		Heat energy required to overcome the adsorptive power of the bound water	6,224 J	0.3%
H_3		Heat energy required to heat the residual water in wood	2,329 J	0.1%
H_4		Heat energy required to heat and evaporate the water that is eliminated from the wood	385,734 J	17.7%
H_5	H_{5a}	Heat energy required to heat the air flowing in from outside the dryer	1,762,752 J	81.0%
	H_{5s}	Heat energy required to heat the steam flowing in from outside the dryer	6,713 J	0.3%
H_t		Total of theoretical required heat energy	**2,177,131 J**	**100.0%**

must be designed to optimally match the amount of wood particles to be dried, and the air circulation rate must also be controlled.

3.3. Energy loss and efficiency

The actual consumed energy was measured during drying using a power meter, and was 7,560 kJ. Given the results in Table 2, this equates to 5,383 kJ energy loss or 28.8% energy efficiency. For industrialization this energy loss must be decreased, with consequential increasing energy efficiency, considering the various drying conditions, such as the amount of wood particles to dry, dryer size, air circulation rate, etc.

4. CONCLUSION

The economic feasibility of industrialization of fluidized bed type dryer for wood particles was investigated, and the energy efficiency was evaluated using a pilot scale fluidized bed dryer.

200 g (oven dried weight) of wood particles, with 50% moisture content, were dried for a fixed period and the dried wood recovered and measured. The theoretical required heat energy was calculated and compared to the measured actual consumed energy (7,560 kJ). Final energy efficiency of the pilot scale fluidized bed dryer was 28.8%. The relatively large internal space of the dryer compared to the amount of wood particles dried and the plentiful air circulating meant that most of the consumed energy was used to heat the air flowing into the dryer. Almost 81.0% of the theoretical energy usage was taken heating the air, with only 17.7% heating the water within the particles. This did not compare favorably to other wood drying methods, such as kiln drying of lumber or round timber.

Therefore, when drying wood particles using fluidized bed dryer for the domestic industry, the dryer must be optimally designed for the target amount of wood particles, and the air circulation rate must be appropriate for that dryer size. This would decrease the energy loss, consequently improving energy efficiency.

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