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Experimental and simulation investigations on self-heat recuperative fluidized bed
dryer for biomass drying with superheated steam

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Abstract

An exergy recuperative module was developed and applied to biomass drying. The proposed drying process has an energy consumption 1/20 that of a conventional heat recovery drying system. Experimental work was conducted to confirm the details of the self-heat recuperation technology concept. A high drying rate and a stable heat exchange was found through the experimental drying results. Furthermore, the heat pairing was confirmed in the drying system for the first time.

Keywords: Drying; Self-heat recuperation technology; Steam; Heat pairing

1. Introduction

Global warming is a common problem of concern that every country has made great efforts to solve. Solar energy, hydrogen energy, and CCS process technologies have been developed to minimize the large amounts of CO₂ emitted by fossil fuel combustion processes. The use of biomass has also been promoted in many countries as a solution to the global warming problem. Biomass is considered to be a kind of renewable energy because it is able to store solar energy through photosynthesis using CO₂ as the raw material. Energy conversion processes such as pyrolysis and gasification, combustion and co-combustion with coal, and torrefaction may be used to supply energy from biomass [1-3]. However, biomass residues and wastes, which are readily available in large amounts, cannot be effectively converted by these processes. One of the main reasons for this is their high water content, which usually exceeds 50 wt% (wet basis). A high moisture content makes biomass conversion uneconomical by reducing the heat value of the biomass and increasing its transportation cost.

Drying processes are used to **reduce the water content of** wet biomass to under 10 wt% (wb) [4]. However, **such** biomass drying processes consume **much** energy owing to the high energy required for water evaporation. **The dramatic increases in energy costs caused by the shortage of fossil fuels have motivated the development of many energy-saving technologies for biomass drying** in the past few decades. For example, heat-pump drying, multistage drying, mechanical vapor recompression, and heat recovery by recycling exhausted air and integrating the drying system with other exothermic processes have been developed for energy-saving [5-7]. In existing heat integration drying processes based on pinch technology, **the use of such methods can decrease the furnace load**. Moreover, only part of the heat can be recovered for the minimum temperature difference required for heat exchange [8]. **While** multistage drying **can** make full use of the exhausted heat from the upper stage as the heat supply for the **downstream** stage, a large amount of energy input **is** still **required** during the steam generation period. **This is because** the reaction heat is paired with the heat of steam generation. To minimize energy input during steam generation, mechanical vapor recompression dryer has been developed. Energy consumption could be reduced by using a compressor to increase the exergy rate of the exhausted steam and latent heat can be recovered [9], but the sensible heat of dried material was not recycled. Thus, the current energy-saving processes still require a significant amount of energy input. It is therefore necessary to explore new energy-saving drying processes to improve the overall energy efficiency of biomass drying.

A self-heat recuperation technology has been recently developed **as a better energy-saving method** [10]. Through compression of the effluent stream and optimal heat pairing, each sensible and latent heat in the process could be recirculated, and thus no heater is required **at any stage** of the process. Based on this self-heat

recuperation technology, Liu et al. developed a self-heat recuperative process for biomass drying in air which could save energy to 1/5 of the conventional heat recovery dryer [11]. However, this method still consumed so much energy owing to the use of air as the drying medium, which caused a mismatched heat pairing. Furthermore, a biomass drying plant requires a high drying rate and good system stability, whatever the energy-saving methods used. It is important to investigate the drying rate and system stability experimentally because it is difficult to predict these factors using simulation software. In this study, we aimed to develop an improved energy-saving biomass drying process based on self-heat recuperation technology using steam as the drying medium. The resulting energy consumption was investigated through simulations. A lab-scale biomass fluidized bed dryer was built to confirm the successful operation of the self-heat recuperation technology and the overall drying performance. The results of this work will be useful for future large plant construction.

2. Simulation

2.1. Exergy recuperative biomass drying process

The process diagram for the proposed biomass drying process based on self-heat recuperation technology is displayed in Fig. 1. A fluidized bed dryer, which shortens drying time by the rapid transfer of heat and moisture between solids and gas during particle fluidization, was chosen as the evaporator. Initially, the wet biomass receives sensible heat from the heat exchanger (HX1) and is preheated to the boiling point of water. Subsequently, it is fed to a fluidized bed dryer (HX2), where free water is evaporated. Immersed heat exchange tubes are inserted in the bed such that the compressed steam flowing inside the tubes have latent heat exchange with the water

in the biomass. Then, the exhausted steam is split into recycled steam and purged steam, equivalent to the evaporated free water. The purged steam is then compressed, and recycled for water evaporation and biomass preheating. The dried solid has heat exchange with the cold wet biomass in HX4, and then is cooled to ambient temperature.

2.2. Simulation conditions

Analysis of the energy consumption of the drying processes was conducted using PRO/II ver. 9.1 software (Invensys Corp.). The wet biomass inlet flow rate was set to 5000 kg h⁻¹ with an initial moisture content of 75 wt% (wb). The fluidized bed was square with a side length of 4.0 m and a height of 4.0 m. The bed voidage at the minimum fluidization velocity was 0.42. The Soave-Redlich-Kwong method was used as the model for calculation of the drying process. Heat exchange is concurrent in the fluidized bed dryer and countercurrent in other heat exchangers, and the minimum temperature difference in each heat exchanger is 10 K. Adiabatic efficiencies of the compressor and blower are both 80%. The blower is used for particle fluidization. Its power consumption was determined from the pressure loss in the fluidized bed Δp_f , which included the pressure drop across the bed Δp_b and the pressure drop across the distributor Δp_d . The pressure drops were calculated according to the equation proposed by Kunii and Levenspiel [12]:

$$\Delta p_f = \Delta p_b + \Delta p_d \quad (1)$$

$$\Delta p_b = (1 - \varepsilon_{mf})(\rho_p - \rho_g)H_b \frac{g}{c} \quad (2)$$

$$\Delta p_d = 0.4\Delta p_b \quad (3)$$

where ε_{mf} is the bed voidage, ρ_p and ρ_g are the densities of particles and gas,

respectively, H_b is the bed height, and c is the conversion factor ($1 \text{ kg m N}^{-1} \text{ s}^{-2}$).

3. Experiment

Wet sawdust (Echigo cedar, diameter 0.34–0.5 mm, density 0.28 g/cm^3) was used as the biomass material to be dried in this work. Silica sand was mixed with the sawdust because sawdust particles of any moisture content are poorly fluidized in a single component system. Mixing and fluidization performance were first investigated in the fluidized bed dryer with air as the drying medium. Based on the results, an optimal diameter and weight ratio of silica sand to sawdust was determined for the batchwise and semicontinuous experiments using steam as the drying medium. The drying behavior of the sawdust in the fluidized bed dryer was investigated, and the system stability of heat exchange was also checked in the fluidized bed under semicontinuous operation.

3.1. Experimental setup

Based on the above concept, a laboratory-scale fluidized bed dryer was set up as shown in Fig. 2. The main body was made of stainless steel, and contained some inspection windows to allow the observation of particle fluidization. The fluidized bed dryer had a square cross-section with a side length of 0.2 m and a height of 1.0 m. This size was necessary to allow study of the heat transfer and particle fluidization in the fluidized bed. A steam generator (OSG-150T, Osaka Denki Co., Japan) with a maximum steam generation capacity of 15 kg h^{-1} was added to generate steam as the fluidization medium. The generated steam was heated using a heater placed at the entrance of the fluidized bed dryer to achieve the desired temperature, and the flow rate of the steam was measured using a steam flow meter. To simulate the compressed

steam from the moisture in the biomass, another steam generator (OSG-40, Osaka Denki Co. Japan) was added to **pass** compressed steam through the heat transfer tubes in the fluidized bed dryer to provide evaporation heat. A gas-liquid separator was added at the outlet of each steam generator to separate the condensed water in the saturated steam from the steam generator. The condensed water from the heat transfer tubes in the fluidized bed was separated from the steam after heat exchange with the biomass in the fluidized bed dryer, and collected in a water tank. Three K-type thermocouples were installed in the fluidized bed (top, middle, and bottom) **to measure the temperature distribution across the bed**. The pressure and temperature at each pipe and at different heights in the fluidized bed dryer were measured **using** pressure transducers and **thermocouples**, respectively. The **resulting** data **were** recorded by a data logger (NR1000 Keyence Co., Japan). Phenolic foam insulation was fixed around the surface of the fluidized bed to prevent heat loss from the bed to the environment. The temperature of the bed surface **was maintained within** the range of 100–120 °C with an accuracy of 1 K by **wrapping** ribbon heaters around the drying chamber.

3.2. Experimental procedure

3.2.1. Mixing and fluidization performance

Because of their peculiar shape and low density, biomass particles are subject to extensive channeling and slugging and cannot be fluidized properly in normal fluidized beds, even at high gas velocities [13-15]. **Thus, pure** biomass particles cannot be fluidized alone without adding silica sands or mechanical assistance. In this study the biomass was co-fluidized with silica sand to assist its fluidization. The mixing and fluidization performance of the silica sand and sawdust was investigated

to find the optimum ratio for stable operation in the fluidized bed dryer. Mixtures of sawdust and silica sand with different diameters, shown in Table 1, in various ratios (weight of sawdust to total weight) were fluidized in the fluidized bed dryer. The resulting pressure drops in the fluidized bed were investigated at different gas velocities to determine the minimum fluidization velocity of each silica sand and sawdust mixture. In adequate fluidization, a bubbling regime is observed without the formation of channels at increasing gas velocities [15]. With mixing ratio further increasing, experiment was stopped when the poor fluidization occurred, which was determined visually and from the occurrence of a pressure drop across the bed.

3.2.2. Batch experiment

Biomass drying with steam is commonly conducted at high temperatures. To reduce the exergy loss during the drying process using self-heat recuperation technology, a low drying temperature near the boiling point of water is required. However, this may cause steam to condense easily on the particles surface. There are few reports on the drying of biomass with steam in a fluidized bed dryer at low temperature [16, 17]. To confirm the possibility and drying rate, we first conducted batch-wise biomass drying experiments.

Before the steam drying experiment, the fluidized bed was preheated with hot air to over 100 °C to prevent the steam condensing when it entered the fluidized bed. Then, the fluidization medium was switched from air to steam. Based on the simulation results, the generated steam was initially preheated to 120 °C before it entered the fluidized bed dryer. In these batch experiments, for better control and investigation of the amount of energy input, we first used three sheathed heaters (diameter 6 mm, length 120 mm) installed inside the fluidized bed dryer at a height of 25 mm above

the distributor to simulate the compressed steam used as the heat source for drying. After the bed temperature was stable at around 110 °C, the wet sawdust was added into the fluidized bed. The drying process began to progress and water in the sawdust was evaporated into the fluidizing/drying medium. Samples of the mixture of sawdust and sand were taken from the fluidized bed during the drying process. After sampling was completed, the sawdust was separated from the sand using a mesh sieve and weighed before being placed into an oven. Then, an amount of sand equal to the amount removed from the fluidized bed dryer was previously heated in an oven at 103 °C and then added to the fluidized bed to maintain a constant amount of sand in the dryer. The dried sawdust sample was heated for 24 h at 103 °C and then weighed again. The moisture content of the sawdust, W_{wet} , was calculated as follows:

$$W_{\text{wet}} = \frac{M_1 - M_2}{M_1} \times 100\% \quad (4)$$

where M_1 is the weight of the sampled dried sawdust and M_2 is the weight of the sampled sawdust after being kept in the oven for 24 h.

3.2.3. Semicontinuous experiment

In the semicontinuous experiment, we changed the heat source from sheathed heaters to compressed steam to investigate system stability and heat pairing between the evaporation heat and condensation heat of the steam. In the semicontinuous experiment, 150 g sawdust with a water content of 61.8 wt% (wb) was fed intermittently into the fluidized bed dryer at intervals of 8 min. Meanwhile, the dried sawdust was discharged with the silica sand from the exit tube at an interval of 15 min. Compressed steam with a pressure of 190 kPa at 119 °C flowed through the heat exchange tubes (as shown in Table 2) in the fluidized bed and supplied steam condensation heat for water evaporation. The sampling time was controlled by

opening and closing the door at the outlet. Condensed water was collected through a tank and weighed after the drying process had completed. Discharged sand–sawdust mixture was moved to the oven, and the moisture content of the dried sawdust was measured using the same method as that described above. The drying experiment was typically conducted for 180 min but was stopped in cases of poor fluidization, which was determined visually and from the temperature distribution across the bed.

4. Results and discussion

4.1. Simulation results

Fig. 3 shows that our proposed exergy recuperative drying system with superheated steam has great energy-saving potential. The drying of 5000 kg h^{-1} wet biomass from 75.0 to 31.5 wt% (wb) water content using the conventional heat recovery drying process has an energy consumption of 2159.9 kW, while use of the self-heat recuperative drying system with air reduces the energy consumption to 540.9 kW. In contrast, the energy consumption of the self-heat recuperative drying system with steam was only 100.2 kW, less than 1/20 that of the conventional heat recovery drying system and 1/5 that of the self-heat recuperative drying system with air. In the self-heat recuperative drying system with air, the heat exchange temperature difference between the hot and cold streams was high because the hot stream temperature is greatly increased as the air-steam mixture is compressed. In the self-heat recuperative drying system with steam, energy consumption can be dramatically decreased owing to the good heat pairing in the drying process. This can be observed from the temperature-heat diagram shown in Fig. 4, in which the temperature difference between the cold and hot streams was always maintained at the minimum temperature difference of the heat exchanger during both the preheating and

evaporation stages.

The specific chemical exergy of biomass is calculated to be 19.9 MJ kg^{-1} using the following calculation proposed by Song et al. [18]:

$$e = 1812.5 + 297.241C + 615.788H + 20.356O + 20.652N + 99.738S - T_0 S_{\text{OM}}^0 + E_{\text{ash}}^{\text{CH}} - T_0 S_{\text{ash}}^0 \quad (5),$$

where C , H , O , N , and S are the contents of C, H, O, N, and S elements in the dry biomass, respectively, in wt %. S_{OM} is the specific standard entropy of organic matters in 1 kg of dry biomass. $E_{\text{ash}}^{\text{CH}}$ is the chemical exergy of ash, and S_{ash}^0 is the standard entropy of ash. Thus, the effective energy contained in 5000 kg h^{-1} biomass with a water content of 75.0 wt % (wb) is calculated to be 16363 MJ h^{-1} , and that in the same amount of dried biomass is 23477 MJ h^{-1} . The energy consumption of the self-heat recuperative drying system with steam was 360 MJ h^{-1} . Therefore, compared with the energy held by the dried biomass, the input energy for drying was relatively low, about 1.5 % of the energy in the biomass. This result validates the merits of our designed biomass drying process.

4.2. Experimental results

4.2.1. Mixing and fluidization performance

Three different diameters of silica sand were used to investigate the hydrodynamic performance of co-fluidized wet sawdust. The results showed that the diameter of the sand had an important effect on the fluidization performance. The minimum fluidization velocity of each silica sand and sawdust mixture at different mixing ratios is shown in Fig. 5. The minimum fluidization velocity was determined from the relationship between the velocity of the drying gas and the pressure loss in the bed. Good mixing and fluidization performance was achieved for each diameter of silica sand when the mixing weight ratio was between 0 and 0.05. However, channeling

occurred in the mixture of sawdust and silica sand ($d = 0.1$ mm) when the weight ratio was increased to 0.07, signified by a trough in the pressure drop curve (Fig. 5). The bed did not return to a packed bed conformation and continued to exhibit channeling until the gas velocity became zero. In the case of silica sand ($d = 0.34$ mm), sawdust and silica sand were co-fluidized well at a low mixing ratio. However, the binary mixture was difficult to co-fluidize when the mixing ratio was larger than 0.05, owing to the limitations of the blower used in our experimental device. In the case of silica sand ($d = 0.154$ mm), the mixing and fluidization performance was good even at a high mixing ratio. Based on the above results, silica sand with a diameter of 0.154 mm was chosen for use in our steam drying experiments. The minimum fluidization velocity of the mixture of 0.154 mm diameter sand and wet biomass was also calculated from equations recommended by Bilbao et al. [19] as:

$$u_{vf} = u_{pk} - (u_{pk} - u_f) X_f ; \quad (6)$$

$$u_{pk} = 50 d_{pk}^{0.84} ; \quad (7)$$

$$X_f = \frac{x_f}{x_f + (\rho_f / \rho_{pk})(1 - x_f)} ; \quad (8)$$

where u_{vf} is superficial velocity of gas where both components in a binary mixture are fluidized, u_{pk} is fictitious minimum fluidization velocity of sawdust, and u_f is sand volume fraction in bed. d_{pk} is the particle size of packed component, and x_f is weight fraction of fluid and packed component in binary mixture. ρ_f and ρ_{pk} are density of sand and sawdust, respectively. Fig. 6 shows the approximate values of the calculated and experimental values obtained when defining a higher value of u_{pk} of 0.71.

4.2.2. Batch experiment

The sawdust was preheated to 80 °C to avoid condensation of the steam condensation on the sawdust surface leading to an increased drying time when sawdust was put into the fluidized bed dryer. The steam flow rate was 4.1 kg h⁻¹ with a velocity of 7.79 cm s⁻¹. The steam inlet temperature was 120 °C with an absolute pressure of 160 kPa. The temperature at the top, middle, and bottom of the fluidized bed were monitored during the drying process. The temperature difference among the levels was very small, indicating a homogenous state in the fluidized bed. As shown in Fig. 7a, in our system, the biomass could be fluidized and dried at a very low temperature of 101.5 °C without condensation of the steam. This low bed temperature reduced exergy loss during the heat exchange process. The bed temperature dropped from 112 °C to 101.5 °C when the sawdust was put into the bed and was maintained at 101.5 °C for 27 min during the free water removal. Because the energy supply was used as the heat for water evaporation, the bed temperature kept constant during the free water drying process. The bed temperature began to increase during the removal of adsorbed or chemically bound water from the biomass. The bed temperature was a little higher than the boiling point of water owing to the presence of a temperature difference for heat transfer from the sand to the biomass particles. Furthermore, the energy input increased to 240 W, and the constant drying rate period was shortened from 27 min to 12.6 min (Fig. 7b). Drying time may be shortened by increasing the number of heaters. In the case of indirect steam fluidized dryer, energy supply was from the steam condensation, thus, a similar effect could be achieved by increasing the amount of heat exchange surface in the indirect steam fluidized bed dryer. When the energy input was increased to 360 W, the constant drying rate period almost disappeared owing to the large amount of heat supply (Fig. 7c). The constant rate period was significantly affected by the amount of energy input (W) into the dryer,

compared with its effect on the fall rate period. Although the bound water removal time also decreased with increasing input energy, the reduction was not as dramatic as that for the free water removal stage. This was because the mass and heat transfer rates were high in the fluidization bed dryer; thus, the free water in the biomass could be removed quickly. During the removal of bound water, the physical properties of the sample such as water diffusivity and thermal conductivity affected the drying performance. Thus, the time taken for the bound water to be removed was almost the same as that for the removal of the free water, despite the initial amount of bound water in the biomass being less than half that of the free water.

4.2.3. Semicontinuous experiment

A semicontinuous experiment was conducted to investigate the exergy recuperative drying system stability and heat pairing. Fig. 8 shows that the bed temperature dropped near to the boiling point at the time of wet biomass intake as a result of the evaporation of free water. Afterwards, the temperature quickly returned to the mean temperature owing to the good mixing in the fluidized bed. The temperature difference between the top and bottom levels in the fluidized bed was very small, indicating good particle mixing during the fluidization.

The pressure and temperature of the compressed steam at the inlet and outlet of the heat exchange tubes were also monitored. A consistent temperature and pressure of the air–steam mixture at the outlet of heat-exchange tubes were confirmed, as shown in Fig. 9. The mean values of the outlet absolute pressure and temperature of the steam were about 182 kPa and 118 °C, respectively. The drops in pressure and temperature through the 18 immersed tubes were about 8.0 kPa and 1.0 K, respectively. The pressure drop was due to the steam condensation in the tubes. The

temperature difference between the inlet and outlet heat exchange tubes was 1.0 K, indicating that the mainly latent heat exchange occurred. The constant pressure and temperature drop indicated that the heat exchange between the compressed steam and the wet biomass was consistent. Sawdust was sampled and its water content measured every 15 min. Fig. 10 shows that the water content of the sawdust was constant during the drying process, maintaining a low value of 2.5 wt% (wb). The amount of condensed water from the heat exchange tubes collected in the tank was 1040 g, while the water evaporated from the biomass was calculated to be 1092 g based on the water content of the dried biomass. This means that almost all of the evaporation heat of the water in the biomass was supplied from the condensation heat of the steam obtained from water in the biomass. Thus, a good heat pairing was formed in the fluidized bed dryer for latent heat exchange.

5. Conclusions

A novel exergy recuperative module was applied to a biomass drying system. Energy consumption was saved to the 1/20 of conventional heat recovery drying system in the self-heat recuperative fluidized bed dryer. A good stability in fluidized bed dryer based on simulation conditions is confirmed. The batch experiment showed that biomass could be dried with steam near the boiling point at the operation pressure in the fluidized bed dryer with a high drying rate. Increasing the energy supply by increasing the amount of heat exchange surface could shorten the drying time to less than half of the drying process, especially for the constant drying period. The heat exchange stability in the fluidized bed was good. Almost all the evaporation heat was supplied from the water condensation heat, confirming a good heat pairing in our developed dryer design.

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Table 1. Some relevant properties of the solids used in this study

	Diameter d (mm)	Density ρ (g/cm ³)	U_{mf} (cm/s)
Sand (No.7)	0.10	2.62	1.16
Sand (No.6A)	0.15	2.62	3.03
Sand (No.6)	0.34	2.59	8.78
Sawdust	0.34~0.5	0.28	-

Table 2. Properties of heat transfer tubes immersed inside fluidized bed dryer and steam

Tube properties	Values
Tube material	SUS316 (18% Cr, Ni 12%, Mo 2.5%, 67.5% Fe)
Thermal conductivity (W mK ⁻¹)	16.7
Inner diameter (mm)	8
Outer diameter (mm)	10
Arrangement	Horizontal
Pitch distance (mm)	50
<i>Compressed steam</i>	
Inlet temperature (°C)	119
Inlet pressure (kPa)	190

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7a

Figure 7b

Figure 7c

Figure 8

Figure 9

Figure 10