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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 were found through the experimental drying results. Furthermore, the heat pairing was confirmed in the drying system for the first time.

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 CO_2 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 CO_2 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

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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 busing 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 slide 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]:

$$\Delta p_{\mathrm{f}} = \Delta p_{\mathrm{b}} + \Delta p_{\mathrm{d}} \tag{1}$$

$$\Delta p_{\mathrm{b}} = (1-\varepsilon_{\mathrm{mf}})\left(\rho_{\mathrm{p}}-\rho_{\mathrm{g}}\right)H_{\mathrm{b}}{}^{g}/{}_{c} \tag{2}$$

$$\Delta p_{\mathrm{d}} = 0.4\Delta p_{\mathrm{b}} \tag{3}$$

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 kg m N^{-1} 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

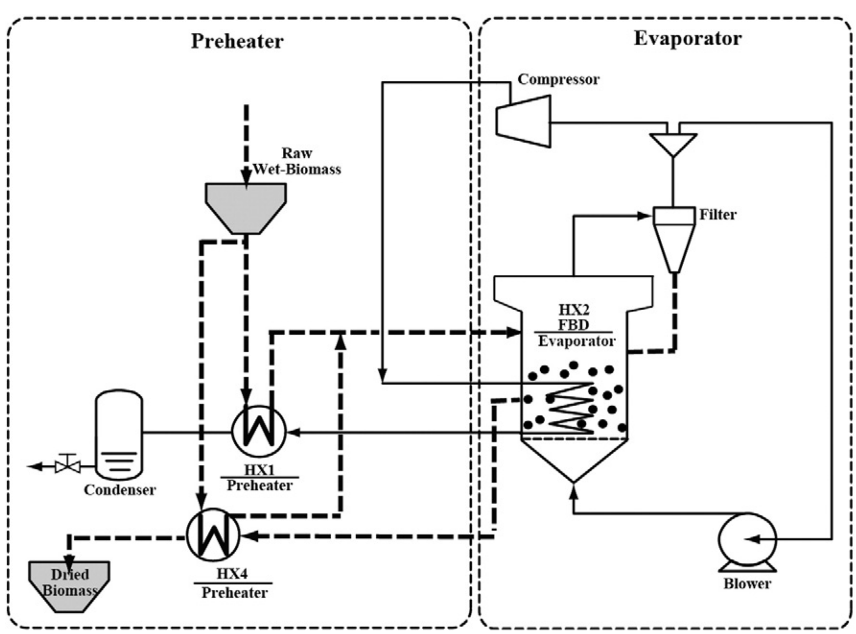

Fig. 1. Exergy recuperative biomass drying process.