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Novel fluidized bed dryer for biomass drying

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ABSTRACT

Biomass drying is performed mainly in rotary dryers, which occupy a large footprint. To explore the efficient drying of biomass, a fluidized bed dryer was proposed. Good circulation of biomass particles could be established in the fluidized bed without the use of inert particle or mechanical aids. The initial moisture content of the input sawdust affected its fluidization performance. For the drying of sawdust of high-moisture content, the fluidization behavior could be divided into three stages: partial fluidization, full fluidization with increasing drying rate, and full fluidization with decreasing drying rate. A high drying rate could be achieved because of the fast mass and heat transfer rate in the fluidized bed. The fluidized bed dryer has a drying performance similar to the binary mixture fluidized bed dryer but more compact, and requires no separation of dried biomass particles from the inert bed particles.

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1. Introduction

Biomass is a renewable primary energy source because of its low net carbon dioxide emissions. It may be sustainable if its economic, environmental, and social impacts are properly managed. Biomass shows great potential as a sustainable feedstock source for combustion and co-combustion with coal, syngas production by gasification, bio-oil production by pyrolysis, solid formation by carbonization and bioethanol production by fermentation [1–3]. Biomass has a low energy density compared with traditional fossil fuels. This is mainly because of its high moisture content, which commonly exceeds 50 wt.% (wet basis, wb). This moisture content limits its application as an alternate fuel because of the resultant high transportation costs, storage difficulties and reduced thermal efficiency during energy conversion. Biomass moisture content should be decreased to 8–10 wt.% (wb) prior to densification and energy conversion for economic use [4]. Hence, biomass drying is used to increase the energy density so as to deliver the bulk and widespread biomass to bioconversion plants.

Many kinds of drying systems have been developed for biomass drying such as the conveyor dryers, rotary dryer of single or multiple passes, and the fixed and moving bed dryers, among which rotary dryers are the most common [5–8]. However, because of their operating conditions, horizontal configuration, and low-heat transfer rate, existing biomass dryers are usually large and occupy a large footprint [9]. To improve the economy of biomass-based processes prior to transport, it is desirable to have a compact and economical dryer. Fluidized beds have a high heat transfer rate and exhibit excellent solid mixing and uniform temperature distribution [10]. The fluidized bed dryer could thus be a potential compact dryer for biomass drying. Unfortunately, one of the challenges for biomass drying in fluidized beds is to achieve good gas–solid contact and bed stability. 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 [11–13]. An inert material such as silica sand, glass spheres, alumina, or calcite is usually used to facilitate fluidization of the biomass particles, which are present only in a small fraction [14]. The introduction of inert particles into the fluidized bed may contaminate the dried biomass product and increase the pressure drop through the bed. Mechanically assisted fluidized beds such as vibrated or agitated and pulsed fluidized beds have been used for biomass drying without the addition of inert particles [15,16]. However, the increased equipment complexity may result in operational problems and increase the cost of the device. Biomass could also be dried in spouted beds at high gas velocities [17]; however, the heat transfer rate decreases because of the inefficient gas–solid contact compared with fluidized beds [18].

The aim of this work is to explore a compact and economical dryer for biomass drying by using the advantages of high mass and heat transfer rates in the fluidized bed. A new fluidized bed dryer was proposed for biomass drying with inclined micro-jet distributor design. During drying, the fluidization behavior of the pure biomass particles would be affected by evaporation and wet regions on the surface of the particles and the inter-particle capillary forces. In addition, during the drying process, the fluidization behavior may be altered as the moisture content decreases. Thus, the fluidization performance needs to be

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examined during the drying process. The biomass drying rate also had to be investigated to confirm the drying performance in the proposed fluidized bed dryer. In this work, the effects of air velocity and drying temperature were investigated to evaluate the performance of the fluidized bed dryer.

2. Materials and methods

2.1. Materials and experimental equipment

The sawdust sample, obtained from RONA lumber store in Vancouver, Canada, is a mixture of spruce and fir, with spruce as the main component. The sample was separated into two size fractions of 250–355 and 355–500 μm, respectively, using a Ro-Tap RX94 sieving device (W.S. TYLER Co. Ohio, USA). The solid density of the sawdust measured using a multi-pycnometer (Quantachrome Instruments Co. Florida, USA) was 1388 kg m^{-3}. The bulk density of wet sawdust with 60 wt.% (wb) moisture content was 282 kg m^{-3}.

Batch runs for drying the sawdust were conducted in a stainless steel fluidized bed dryer, 1.5 m tall and 50 mm in diameter, as shown in Fig. 1a. A gas distributor with 30° vertically inclined orifices was designed to achieve a good solid circulation. Twelve holes were located around the peripheral region and two holes in the center with an inclined angle opposite the outer region. As a result, a solid circulation pattern was established with sawdust particles rising in the center, passing through a fountain region and then moving down slowly along the wall. This kept the entire bed of particles in motion as shown in Fig. 1b. Three thermocouples (T1, T2, and T3) were used to measure the temperatures of the inlet gas, fluidized bed, and reactor wall and control the electric heater by means of a proportional integral derivative controller. The pressure drop across the fluidized bed was measured by the pressure difference between the pressure transducer P1 before and after the sawdust input. Dry air from an air cylinder was preheated to the desired temperature before being fed into the fluidized bed. The air flow was measured using a rotameter. As the drying progressed, water in the sample evaporated into the air. A hygrometer (HUMICAP, Vaisala, Finland, with precision of 1.0%) was installed at the fluidized bed dryer outlet to monitor the relative humidity and temperature of the humid air simultaneously. The wall surface of the fluidized bed dryer was maintained at a certain temperature by an electric heater surrounding the outer wall of the fluidized bed. The reactor was insulated to prevent heat loss from the bed to the environment.

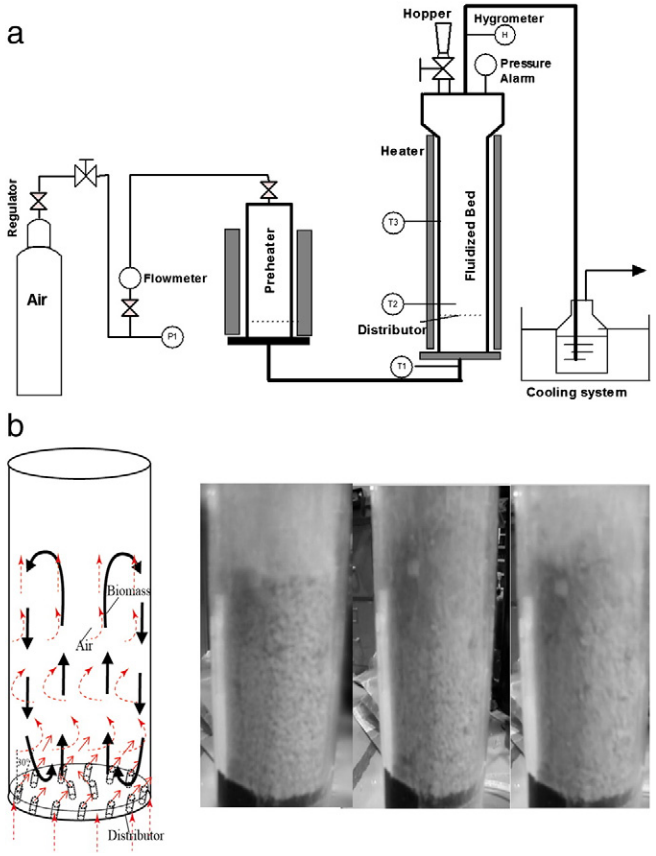

Fig. 1. a. Schematic of fluidized bed drying unit. b. Left: solid circulation pattern in new fluidized bed dryer; right: sawdust (255–500 μm) fluidization in cold model.

2.2. Experimental procedure

The fluidized bed dryer was heated slowly to the targeted drying temperature and kept stable for at least 10 min. Wet sawdust of a particular moisture content was weighed using a balance with precision of 0.1 mg and fed from the top of the fluidized bed. The sawdust was fluidized by air with a predetermined flow over a desired residence time period. During the drying process, water was transferred from the wet sawdust to the air. Since it was difficult to investigate the mass change of the sawdust in the stainless steel fluidized bed during the drying process, the mass loss of wet sawdust, $W_{\rm loss}$, was calculated from the amount of water carried out by the air.

$$W_{\rm loss} = w_n - w_m = m_g \sum_{i=m}^{n} Y_i [g-{\rm water}], \tag{1}$$

where w_n and w_m are the mass of wet sawdust at different times. The drying rate, R_w, is determined by Eq. (2):

$$R_w = \frac{dw}{dt} = \frac{m_g \sum_{i=m}^{n} Y_i}{t_n - t_m} = \frac{m_g (Y_m + Y_{m+1} + \cdots + Y_i)}{t_n - t_m} [g-{\rm water}/\min], \tag{2}$$

where m_g is the amount of air and Y is the specific humidity, which is the ratio of mass of water vapor per unit mass of dry air, as calculated from:

$$Y = 0.622 \left(\frac{p_s}{p - p_s} \right) \quad [g-water/kg-air]. \tag{3}$$

The water vapor saturation pressure was calculated from the Wagner–Pruss equation [19]:

$$\ln\left(\frac{{\rm p_s}}{22.064e6}\right) = 647.096/{\rm T_k} \,(-7.85951783\nu + 1.84408259\,\nu^{1.5} \\ -11.7866497\nu^3 + 22.6807411\nu^{3.5} - 15.9618719\nu^4 \\ +1.80122502\,\nu^{7.5}), \tag{4}$$

where

$$\nu = 1 - {}^{T}\Big/_{647.096}. \tag{5}$$

T is absolute air temperature (K). At the conclusion of the drying cycle, dried samples were collected and their final moisture content, $W_{\rm wet}$, was determined according to the ASTM D4442-07 standard by heating the sample at 103 °C for 24 h in an oven [20], with the moisture content given by

$$W_{\rm wet} = \frac{M_1 - M_2}{M_1} \times 100\% \quad [wt.\%\ wb], \tag{6}$$

where M_1 is the initial sampled dried sawdust and M_2 is final weights of the samples after drying in the oven for 24 h at 103 °C, respectively.

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