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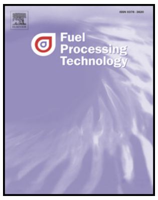

Fluidization and drying of biomass particles in a vibrating fluidized bed with pulsed gas flow

Dening Jia [a], Océane Cathary [b], Jianghong Peng [a], Xiaotao Bi [a,*], C. Jim Lim [a], Shahab Sokhansanj [a,c], Yuping Liu [d], Ruixu Wang [a], Atsushi Tsutsumi [d]

[a] *Department of Chemical and Biological Engineering, The University of British Columbia, 2360 East Mall, Vancouver, BC V6T 1Z3, Canada*
[b] *The École Nationale Supérieure de Techniques Avancées, 828, Boulevard des Maréchaux, 92120 Palaiseau Cedex, France*
[c] *Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[d] *Collaborative Research Center for Energy Engineering, Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan*

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ABSTRACT

Fluidization of biomass particles in the absence of inert bed materials has been tested in a pulsed fluidized bed with vibration, with the pulsation frequency ranging from 0.33 to 6.67 Hz. Intermittent fluidization at 0.33 Hz and apparently 'normal' fluidization at 6.67 Hz with regular bubble patterns were observed. Pulsation has proven to be effective in overcoming the bridging of irregular biomass particles induced by strong inter-particle forces. The vibration is only effective when the pulsation is inadequate, either at too low a frequency or too low in amplitude. Drying of biomass has been carried out to quantify the effectiveness of gas pulsation for fluidized bed dryers and torrefiers in terms of gas–solid contact efficiency and heat and mass transfer rates. The effects of gas flow rate, bed temperature, pulsation frequency and vibration intensity on drying performance have been systematically investigated. While higher temperature and gas flow rate are favored in drying, there exists an optimal range of pulsation frequency between 0.75 Hz and 1.5 Hz where gas–solid contact is enhanced in both the constant rate drying and falling rate drying periods.

1. Introduction

Biomass as a sustainable energy source has regained its popularity during the past decade, mainly attributable to the surging energy demand, supply shortage of fossil fuels, mitigation of greenhouse gases and the increasing public environmental awareness. The total energy supplied from biomass reached approximately 55.6×10^{18} J in 2013 [1]. The international trade of biomass has continued to grow considerably due to a higher demand, particularly for biofuels and wood pellets. Global production and transport of wood pellets already exceeded 23.6 million tonnes in 2013 [1], a 13% increase compared to 2012.

Despite the global prosperity and popularity of biomass, one of the major issues that hinder its further application is the high moisture content. Biomass from various sources generally contains high concentrations of water, which could be either free or chemically bonded. Sawdust directly obtained from sawmills contains over 60% of water, while in general it should be controlled under 13% as high moisture levels normally lead to energy losses, higher risks of mold formation during storage and decreased efficiency and increased emission in combustion. Studies have also shown that for biomass pelletization the ideal moisture content ranges from 5% to 15% on a dry basis [2].

There is no surprise that drying is an essential step for many biomass related operations such as pelletization. Research by Mani et al.[3] revealed that the cost of drying (capital and operation) alone could take up to 20% of the entire pelletization process while hammer mill and pellet mill combined share less than 10%. The energy consumption of biomass drying is approximately 2500–3000 MJ/tonne, whereas the grinding and pelletizing require only 400 MJ/tonne. Therefore, in order to optimize pelletization in terms of process efficiency, energy consumption and product quality, not only is it important but also highly effective to focus on drying. Considering the current scale of operation for pelletization (up to 900,000 tonnes of pellets per year in a single pellet mill from sustainably managed forests [1]), even a small improvement in drying efficiency would significantly alter the outlook.

Compared to traditional biomass dryers (rotary drum dryer, conveyor belt dryer, etc.) fluidized bed offers excellent heat and mass transfer rates, and uniform temperature distribution. However, the unconventional nature of biomass particles such as irregular shape and low bulk density has made biomass fluidization quite problematic [4]. The surface moisture on biomass materials increases the inter-particle forces dramatically [5], at several times bigger than the particle weight, which could lead to channeling, gas bypassing and eventually defluidization. Previous researchers introduced inert particles such as sand to the system to assist fluidization of biomass particles [6–9]. However, it increases ash content in biomass product due to attrition

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* Corresponding author.

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of inert materials, degrading the quality of biomass pellets and subsequently posing serious problems to biomass-powered boilers and turbines that may as a result encounter corrosion, sintering, and slagging, which will require additional maintenance for the removal of deposits and even unscheduled shutdowns [10]. Therefore, fluidized bed dryers without the need of inert particles are greatly favored for drying biomass for the preparation of high quality feedstock (i.e. pellets).

A previous study by Liu et al. [11] showed the potential of fluidized bed drying of biomass without the aid of inert bed materials. Sawdust was dried in a 50 mm ID fluidized bed, the same one used by Li et al. [12], with acceptable gas–solid contact being achieved by the use of a novel distributor with vertically inclined orifices designed to increase radial particle movement.

Besides relying on improving the design of gas distributors and operated at high flow rates, pulsation and vibration have been commonly used in granulation, coating and drying of sticky powders and irregularly shaped agricultural products [13–27]. Pulsed fluidized beds, in which the gas flow rate oscillates periodically with time, have been proven effective in transforming random and chaotic bubble behavior into regular and ordered patterns, improving the fluidization quality of coarse particles greatly [28]. Similar to many mechanical systems, the behavior of pulsation is strongly linked to the frequency. Based on one-dimensional particle motions in incompressible fluid, Molerus [29] interpreted the effect of vibration on the stabilization of particle fluidization, and concluded that 50 Hz was a very effective frequency in reducing gas bypassing. Similarly, Massimilla et al. [30] examined three types of pulsed fluidization at different pulsation frequencies, namely the intermittent fluidization at low frequencies (1.2–2.7 Hz), piston-like fluidization at medium frequencies (2.7–4.8 Hz) and an apparently ‘normal’ fluidization at high frequencies (>4.8 Hz). The piston-like behavior was not observed in the experiments of Wong and Baird [31]. A mathematical model was proposed to offer approximate predictions of the natural frequency of the fluidized bed, around which the pulsation was most effective. DEM simulation by Wang and Rhodes [19,32] confirmed that a frequency of 3–10 Hz would be most effective in ameliorating gas–solid interaction. Periodically formed horizontal gas channels were spotted where they quickly gave rise to regular bubbles, which moved up to the surface of the bubbling bed.

Vibrated fluidized beds bring mechanical vibration energy into conventional fluidized beds to improve the fluidization quality of sticky and cohesive particles and to reduce the consumption of drying medium. Gupta and Mujumdar [33] discussed the hydrodynamics and heat transfer properties in vibrated fluidized beds and derived a power-type correlation for bed pressure drop at minimum fluidization velocity between vibrated and conventional fluidized beds. The promotion of heat and mass transfer rates in vibrated bed was confirmed by Eccles and Mujumdar [34], where the bed-to-surface heat transfer coefficient was measured in a vertically vibrated fluidized bed. By modifying the diffusion term in the conservation equations for drying, Stakić and Urošević [14] successfully simulated drying of fine grains in both fixed and vibrated fluidized beds, and the simulation results were in agreement with the drying performance data obtained from vibrated fluidized beds. It was also found that vibrated beds had a shorter residence time and more uniform temperature distribution.

To improve the fluidization quality and gas–solid contact efficiency of fluidized beds of biomass particles for drying [11] and torrefaction [12], the effect of gas pulsation and bed vibration on the hydrodynamics and drying performance has been investigated in this study in a vibrating fluidized bed. Key parameters such as gas flow rate, bed temperature, pulsation frequency and vibration intensity have been investigated, which are crucial to the design and scaling-up of biomass dryers and torrefiers. Drying rate was adopted as a performance indicator for gas–solid contact efficiency and heat and mass transfer, which is crucial for the development of an energy-efficient fluidized bed reactor for biomass drying and/or torrefaction.

2. Experimental setup

The pulsed fluidized bed with vibration (PVFB) is depicted in Fig. 1. The fluidized bed column was made of Plexiglas with a rectangular cross-section (15 cm × 10 cm, and a height of 1.0 m). It was installed on a vibrating base (Eriez 48A, Eriez Manufacture Co., USA). The vibrating base had a constant frequency of 60 Hz and adjustable amplitude on a scale from 0 to 100%, corresponding to 0 to 0.381 mm of displacement. The drying medium was high-pressure building air. After being regulated by a pressure regulator (AR-40-N04H-Z, SMC, USA), the gas line branched out into two streams. Both streams were equipped with a rotameter (FL6212-V and FL6213-V respectively, Omega, Canada) with needle valves to monitor and control the flow rate individually. The first stream was the pulsating stream, on which a solenoid valve (8210G034-120/60, ASCO Valve, USA) was installed. The open and closing of the valve was controlled by a computer program. In order to reduce the fluctuation of gas flow rate through the rotameter, a surge tank was placed between the solenoid valve and the rotameter. The presence of the surge tank could also maintain a stable supply of drying air during operation. The second stream was the fluidization stream where the flow rate of air was maintained constant. The purpose of this stream was to provide a stable gas flow to keep the bed mobilized. However, previous and preliminary studies have shown that at the same overall flow rate, the steady fluidization stream branched out from the same source of gas supply will dampen the ‘shock’ brought by the pulsation stream and undermine the positive effect of pulsation on the fluidization of biomass particles [35]. Therefore, only the pulsation stream was used for the following experiments. The two streams merged before entering the inline gas heater (AHP-7561, Omega, Canada) controlled by a temperature controller (CN4316, Omega, Canada) so that drying temperature could be regulated. A perforated aluminum plate with 1/8 inch holes and 40% open area was used as gas distributor. A filter bag was installed at the exit of the column to retain the fines.

Along the height of the column, there were six ports for temperature, relative humidity and pressure measurements. The first one was located 25 mm above the gas distributor, and the others were 102 mm apart. Ports 1 and 5 were used to obtain pressure drop across the bed, through a pressure transducer (PX164-010D5V, Omega, Canada). The absolute pressure of the windbox (PX142-005D5V, Omega, Canada) and the column (PX163-005BD5V, Omega, Canada) were also monitored. Temperature in the windbox, dense phase and freeboard were measured by T-type thermocouples. Temperature and relative humidity of the gas phase at both inlet and outlet of the fluidization column were constantly monitored by humidity indicators (HMI41 at inlet, HMT335 at outlet, Vaisala, Finland). The analog signals of the pressure, temperature and the relative humidity were captured by data acquisition devices, so that they could be processed, visualized, and saved through LabVIEW software (Version 2014, National Instrument, USA) onto a PC. LabVIEW was also used to control the solenoid valve through a digital output channel. The specific devices used and sampling rate of the signals are listed in Table 1 below. A high-speed camera (1280 × 720 pixel, *f*/2.2 aperture, 240 frames per second) was mounted in front of the Plexiglas column to capture the transient behavior of the fluidized bed.

Biomass material used in this study, Douglas fir and pine sawdust, was generously donated by Tolko Industries Ltd (Vernon, Canada). Switchgrass was also used. The raw materials were passed through a 3.5 mm sieve to get rid of larger particles unsuitable for fluidization. Particle size distributions after sieving are shown in Fig. 2. Switchgrass has more fines, while pine and fir contain more coarse particles (1.7 mm ~ 3.5 mm). Other basic properties including Sauter mean diameter, bulk and true densities, as well as sphericity are listed in Table 2. True density was measured by a multi-pycnometer (Quantachrome Instruments Co. Florida, USA), and sphericity was measured by an image processing software developed in this group.

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