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Effects of the mass and volume shrinkage of ground chip and pellet particles on drying rates

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ABSTRACT

The effects of varying the mass and volume of ground chip and pellet particles on the particle drying rate were analyzed. Samples of whole pellets and chips were hammer milled using a 3.2 mm screen and the ground chip and pellet particles were found to have similar size distributions, although the pellet particles were denser and more spherical than the chip particles. Prior to drying, water was added to the particles to obtain 0.10, 0.30, 0.50, 0.70, and 0.90 moisture contents (on a dry mass basis). The moistened particles were subsequently dried in a constant temperature thin layer dryer set at 50, 100, 150, or 200 °C under dry pure nitrogen, dry compressed air, or atmospheric air. The chip and pellet particles exhibited similar degrees of shrinkage, but the pellet particles underwent a greater reduction in their bulk volume during drying. It appears that the more spherical pellet particles are prone to shrinkage in more than one direction, whereas the needle-like chip particle shrink only in one direction. A variable radius first order drying model was found to fit the experimental data better than a fixed radius model.

Introduction

Wood chips and pellets are two forms of woody biomass that are commonly employed in pyrolysis or combustion applications. Wood pellets provide a convenient form of biomass because they have superior handling, storage, and feeding properties (Biagini, Narducci, & Tognotti, 2008; Carlson, Tompsett, Conner, & Huber, 2009; Erlich, Björnbom, Bolado, Giner, & Fransson, 2006; Miccio, Barletta, & Poletto, 2013). It is recommended that biomass feedstock is crushed to reduce the particle size to 2 mm or less so as to obtain more efficient thermal conversion of the material (Bridgwater, 2012; Bridgwater & Peacocke, 2000; Czernik & Bridgwater, 2004; Demirbas, 2004; Isahak, Hisham, Yarmo, & Yun Hin, 2012; NikAzar, Hajaligol, Sohrabi, & Dabir, 1996). During direct heat generation, wood particles are combusted in hot atmospheric air (Van de Velden, Baeyens, Dougan, & McMurdo, 2007), while during pyrolysis applications, the reaction takes place under either oxygen-free or oxygen-deficit conditions. In the latter cases, atmospheric air is typically replaced with nitrogen. Crushed chip or pellet particles are exposed to a drying stage during the initial phase of pyrolytic reactions (Bridgwater, 2012; Butler, Devlin, Meier, & McDonnell, 2011; Pang & Mujumdar, 2010; Uslu, Faaij, & Bergman, 2008; Vamvuka, 2011), and the literature shows that the particle size (Gómez-de la Cruz, Cruz-Peragón, Casanova-Peláez, & Palomar-Carnicero, 2015), drying temperature (Chen, Zheng, & Zhu, 2012; Gómez-de la Cruz et al., 2015; Wan Nadhari, Hashim, Danish, Sulaiman, & Hiziroglu, 2014), relative humidity of the drying gas (Sigge, Hansmann, & Joubert, 1998; Tapia-Blácido, Sobral, & Menegalli, 2005), and heating rate (Chen, Zhang, & Zhu, 2012; Li & Kobayashi, 2005) all affect the rate of moisture loss. In addition, the particle density can influence the rates of heat and mass transfer inside the particles. Previous research (Rezaei, Yazdanpanah, Lim, Lau, & Sokhansanj, 2016) has shown that, at similar sizes, ground pellet particles are denser than ground chip particles. Rezaei, Lim, Lau, Bi, and Sokhansanj (2017) have also demonstrated that, under dry nitrogen, water diffuses inside pellet particles at a lower rate than inside chip particles, and consequently a prolonged drying process is expected.

The drying rate of wood is also affected by changes in the particle dimensions, because wood is a hygroscopic, porous substance that tends to contract during the removal of internal moisture. This contraction is typically expressed by a shrinkage coefficient, based on the change in a given dimension divided by the initial dimension (Mujumdar, 2006). The dimensional variation (that is, shrinkage or swelling) of wood is an important physical property that must be well understood to ensure efficient utilization of this material in

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Nomenclature

D	Moisture diffusion coefficient, m^2/s
d_i	Mean diameter of particles retained in the i^{th} sieve interval, mm
d_{sv}	Mass-averaged particle size, mm
$d_{p,dry}$	Average particle size of dry particles, mm
$d_{p,moist}$	Average particle size of moist particles, mm
k	Drying rate constant, min^{-1}
k_0	Pre-exponential factor, min^{-1}
m_b	Bulk mass of particles, g
m_p	Mass of particles, g
M_0	Initial moisture content, kg water/kg dry material
M	Instantaneous moisture content, kg water/kg dry material
M_e	Equilibrium moisture content, kg water/kg dry material
MR	Moisture ratio
R	Universal ideal gas constant
S_b	Bulk shrinkage coefficient with respect to bulk volume
S_p	Particle shrinkage coefficient with respect to average particle size
T	Temperature, °C
V_b	Bulk volume of particles, cm^3
V_p	Volume of particles, cm^3
$V_{b,dry}$	Bulk volume of dry particles, cm^3
$V_{b,moist}$	Bulk volume of moist particles, cm^3
x_i	Mass fraction of particles retained in the i^{th} sieve interval
ε	Bulk porosity
ρ_b	Bulk density, g/cm^3
ρ_p	Particle density, g/cm^3

thermal or biochemical reactors (Almeida, Assor, & Perré, 2008). Shrinkage is influenced both by the initial moisture content of the particles and by the temperature program applied (Sturm, Vega, & Hofacker, 2014), both of which can modify the particle diameter, specific heat and conductivity (Bennamoun & Belhamri, 2008). Kowalski and Mierzwa (2013) showed that current models for the drying of shrinkable materials require some adjustments, and that purely exponential functions do not adequately describe the process. Thakor, Sokhansanj, Sosulski, and Yannacopoulos (1999) assessed drying rates using a first order mass loss model in conjunction with either a fixed or variable radius. This work demonstrated that the variable radius model better fitted the experimental data. The dehydration of fresh wood has also been shown to lead to contraction in the direction normal to the microfibril orientation, such that longitudinal shrinkage is usually negligible (Mujumdar, 2006). As an example, Mazzanti, Togni, and Uzielli (2012) reported that the longitudinal shrinkage of poplar wood is minimal. Taylor, Plank, Standfest, and Petutschnigg (2013) also showed that the radial and tangential shrinkage values of beech wood are approximately 70 and 30 times the longitudinal shrinkage value, respectively (Lu, Ma, Zhao, Jia, & Wang, 2016).

The literature shows that the extent and direction of shrinkage depends on the particle structure and orientation of fibers rather than on the initial moisture content. Microstructural analysis of ground chip and pellet particles in previous research (Rezaei, Lim, Lau, & Sokhansanj, 2016) has demonstrated that the fibers of chip and pellet particles are oriented in the longitudinal direction and randomly, respectively, meaning that these two types of particles should exhibit different shrinkage behavior. However, there is currently limited information regarding the comparative shrinkage and drying behavior of chip and pellet particles. Despite the large number of studies regarding wood shrinkage, the relationship between the structure of a particle and its shrinkage is still unclear. The objective of the current study was therefore to determine the moisture and dimensional changes of ground chip and pellet particles (<2 mm) over a range of initial moisture levels and under various drying conditions. Pine wood, the most prevalent softwood in North America, was selected as the species of interest in this work.

Material and methods

Sample preparation

Pine wood chips ($30 \times 30 \times 5$ mm) prepared for pulping and commercially-produced pine wood pellets (diameter of 6 mm and lengths of 12–24 mm) were supplied by Fiberco Inc. (North Vancouver, BC, Canada). Upon receipt, the pine chips were dried to a moisture content of 4%–5% in a THELCO laboratory precision oven (Model 6550, Thermo Electron Corporation, USA) at 80 °C. After cooling, the dried chips were crushed in a hammer mill (model 10HMBL, Glen Mills Inc., USA) equipped with a screen with 3.2 mm circular perforations. The moisture content of the as-received commercial pellets was 5% and so they were not dried, but simply ground using the same hammer mill and screen size as employed with the chips.

Pre-determined quantities of water were sprayed onto the particles to adjust their initial moisture contents (M_0) to 0.10, 0.30, 0.50, 0.70 and 0.90 (on a dry mass basis). The moistened particles were subsequently stored in sealed containers and kept in a refrigerator at approximately 4 °C for at least three days to ensure a uniform moisture distribution prior to drying tests.

Particle dimensions

Mechanical sieving

Particle size distributions were determined using mechanical sieving and laser diffraction techniques, applying the procedure provided in ASABE ANSI Standard S319.3. Mechanical sieving was performed in conjunction with a tap sieve shaker (Ro-Tap RX 94, Tyler, USA) with sieves having 0.25, 0.5, 1.0, 1.4, 2.0, and 2.8 mm perforations. The shaker subjected the samples to oscillation and tapping for 10 min and the mass-averaged particle diameters were calculated using Eq. (1) (Tannous, Lam, Sokhansanj, & Grace, 2013):

$$d_{sv} = \frac{1}{\sum x_i/d_i}, \quad (1)$$

where x_i is the mass fraction of particles retained in the i^{th} interval between two sieves of mean diameter (d_i).

Laser diffraction

A Malvern Mastersizer (Series 2000, Malvern Instruments, UK) equipped with a dry measurement module (Scirrocco series) was used to obtain the size distributions and average particle sizes of the specimens over the range of 0.02–2000 μm, based on laser diffraction. In each trial, a quantity of particles with a mass of several grams was analyzed in triplicate.

Image processing

A representative quantity of particles was randomly selected from each sample and observed using a microscope. Photographic images of these specimens were thresholded and analyzed using an image processing software package (ImageJ ver. 1.49h, National Institutes of Health, USA). The dimensions (width and length) of single particles were measured via an ellipse fitting technique and

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