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Advances in Woody Biomass Drying by Taking Advantage of Surface Properties

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Abstract. *Comprehensive models for grain drying have been derived using critical data available from literature dating back to Shedd's 1953 work on pressure drop. Although dryer design data for grains and many industrial materials are known, Forest Concepts has developed data and evidence that biomass feedstocks are sufficiently unique that published design data is not applicable. Adaptations of grain models to woody biomass are difficult as many of the coefficients used in the models are unknown. Further, typical grain drying temperatures, around 65°C, are well below the "low" temperature of 100°C often targeted in cellulosic feedstock preparation. Forest Concepts is developing a model to better understand wood biomass drying, particularly in the context of conversion processes. Experimental data shows that the drying rate of Crumbles® precision particles is increased by nearly 100% when compared to equivalent traditional wood particles by taking advantage of biological properties. Checked surface properties of Crumbles® particles expedited diffusion rate of liquid to the wood surface thereby reducing total energy cost of drying. Expedited drying creates an opportunity for smaller dryers at reduced capital cost for equivalent throughput.*

Keywords. Biomass, Feedstock, Preparation, Drying, Low temperature, Surface properties

Introduction

Wood drying may seem like it should be a well understood, mature technology. However, we have found that much of the available technology does not directly apply to particle geometries other than those, like chips or traditional pellet furnish, for which a dryer has been previously designed (Mujumdar 2007). Dryer design data for grains and many industrial materials are known, drawn from critical data dating back to Shedd's 1953 work on pressure drop (Shedd 1953). Adaptations of grain models to woody biomass present substantial challenges because many of the coefficients necessary for modeling wood drying are still unknown. Further, the consensus of wood-to-ethanol conversion technology experts is that the maximum drying temperature of wood particles should be "low", near 100°C, which is between the range of temperatures typically used in either wood drying or grain drying. Low-temperatures and energy efficient drying is imperative because it avoids thermally induced recalcitrance in feedstocks destined for biochemical conversion and reduces the loss of volatile components (turpines, etc.) for feedstocks destined for thermochemical conversion (Brammer and Bridgewater 1999; Luo and Zhu 2011).

New particle shapes and manufacturing abilities, such as Forest Concepts' Crumbles[1] particles and machines, have been developed to meet the feedstock needs of the emerging bioenergy field, but much of the information necessary to design an optimal dryer for the new particles is unavailable. There is also a lack of information to guide an engineering approach to optimizing a particle for drying.

This paper describes a set of experiments developed and conducted to guide our ongoing research into the factors that most affect low temperature wood particle drying.

Safety Emphasis

Fire and explosion prevention are the primary concerns with rapid or prolonged heating of combustible materials, especially when small particles (particularly dust) are present. The research described below aims to inform better design of drying equipment and one important aspect of better design is to protect the health and safety of those nearby when the equipment is in service. To mitigate the risk during the experiments themselves, care was taken to isolate heat sources from flammable materials. Fire extinguishers were kept nearby; since the experiments utilized heated ovens, care was taken to prevent burns from hot surfaces.

Objectives

The overall objective of the current study is to determine information that contributes to our ability to conduct further research so that we can improve upon the design and processing of a wood particle. Our ultimate goal is to develop wood particles that are fully optimized, including all capital and operating inputs, for either cost or energy.

Specifically, the work described herein aims to

1. Provide preliminary research data that enable a better understanding of natural convection drying and forced air drying of small cube shaped wood particles.

2. Provide preliminary research data that enable a better understanding of the influence of size and surface properties on efficient drying of cube shaped wood particles; and

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[1] Crumbles® is a registered trademark of Forest Concepts, LLC, for biofuels.

3. Enable future experimental designs to better understand the effects and importance of the most relevant variables characterizing the wood and air in low temperature wood particle drying.

Experiments

Materials and Equipment

The drying experiments were conducted using three forms of hybrid poplar wood particles:

- Forest Concepts' proprietary 2mm Crumbles particles.
- Forest Concepts' proprietary 6mm Crumbles particles.
- Sawn 6mm wood cubes.

Crumbles particles are produced by processing green industrial grade veneer through Forest Concepts' CrumbleMuncher[2] machine shown in Figure 1. For 2mm Crumbles particles, 2mm thick veneer is processed through a CrumbleMuncher machine fitted with 2mm cutters. For the similar, but larger, 6mm Crumbles particles, 6mm veneer and 6mm cutters are used. In both cases the resulting particles are nearly cubic with two of the three dimensions tightly controlled (+/-20%). The manufacturing process causes substantial tensile failure of the wood in the direction perpendicular to the grain which is tangent to the cylinder of the original log. The failures cause the Crumbles particles to expand and check along the grain of the "cube" and giving them an appearance that is superficially similar to expanded vermiculite.

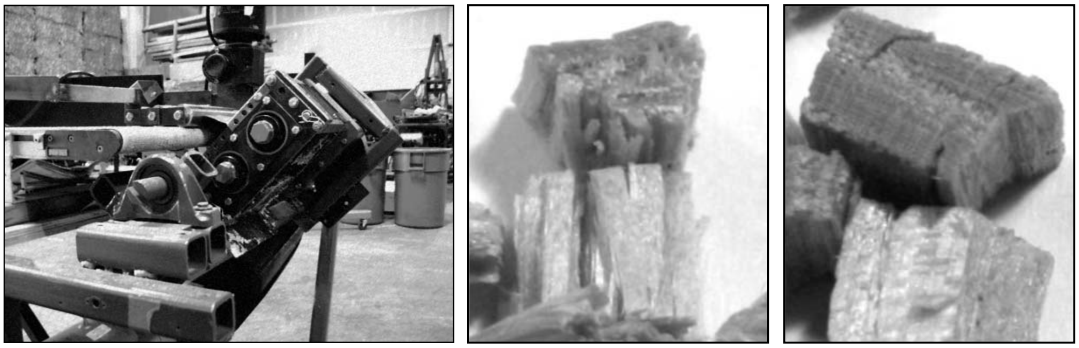

Figure 1. Left) CrumblesMuncher machine. Center) 2mm Crumbles particles. Right) Sawn cubes

The 6mm (nominal size) sawn cubes were hand cut on a band saw from a green hybrid poplar log. The resulting particles were reasonably uniform in both size and shape (6.6+/-0.4mm x 7.0+/-0.4mm x 6.3+/-0.2mm).

Crumbles particles were chosen as the primary experimental material specifically due to their high uniformity and preliminary acceptance in bioenergy markets. Sawn cubes were chosen as a comparative material because they could be made volumetrically and geometrically similar to Crumbles particles in size but with tight grain surface properties more representative of paper chips or traditional pellet furnish.

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[2] CrumbleMuncher™ is a trademark of Forest Concepts, LLC.

The wood particles were stored substantially below fiber saturation point; then immediately prior to each experiment the sample was rehydrated to maximum saturation following Forest Concepts' rehydration protocol[3]. Maximum saturation moisture content of hybrid poplar is about 70%[4] and includes free water between the cells, but not surface water. It is well above the 30% fiber saturation moisture content that does not include free water between cells (Forest Products Laboratory 2010).

The drying experiments were conducted in laboratory ovens[5,6] fitted with the specific apparatus' that are described below. A precision balance[7] was used to determine sample weights (+/- 0.0001g), a hotwire anemometer[8] was used to determine airflow velocities (3.5 m/s +/- 1.5 m/s), and a thermocouple and voltmeter were used to monitor air temperature (100°C +/- 10°C).

Drying Experiments I: Natural Convection

The natural convection experiment was conducted to frame the 2mm particle drying problem, evaluate natural convection drying as a design option, and to guide subsequent experiments. Nominally 2g of wood particles at approximately 75% MC were placed in a single layer on a wire mesh screen in a 100°C laboratory oven without forced convection. The sample was weighed quasi-continuously to determine instantaneous and cumulative drying rates over a period of up to 40 minutes.

Apparatus and procedure

The apparatus used to measure the sample mass throughout the drying period consisted of a lever arm, resting on a precision balance outside of the oven, that suspended a wire mesh basket inside of the oven. The apparatus is shown in Figure 2. The configuration provided a small mechanical amplification of the scale precision. Using calibration masses, the ratio of the scale reading to the sample mass was determined to be 2.206. Scale readings were recorded to the nearest 0.01g.

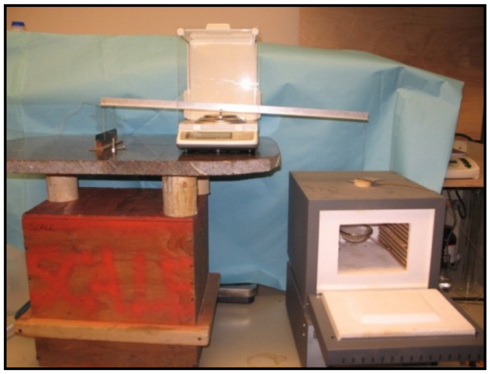

Figure 2. Natural air convection real-time mass measurement apparatus.

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[3] Forest Concepts rehydration protocol is available upon request.

[4] All of the moisture content measurements in this study are reported as wet weight basis.

[5] Thermo Scientific Thermolyne FB48015-60, 1800 Watt (natural convection experiment)

[6] Quincy Labs model 30CG, 1200 Watt (forced convection experiment)

[7] AnD HR-200, 0.0001g accuracy

[8] Dwyer Series 471 Thermo-Anemometer

Results of the Natural Convection Drying Experiment

The single layer of Crumbles particles dried to an “oven dry” state in approximately 20 minutes. Figure 3 shows the drying curves recorded for the single layer natural convection experiment.

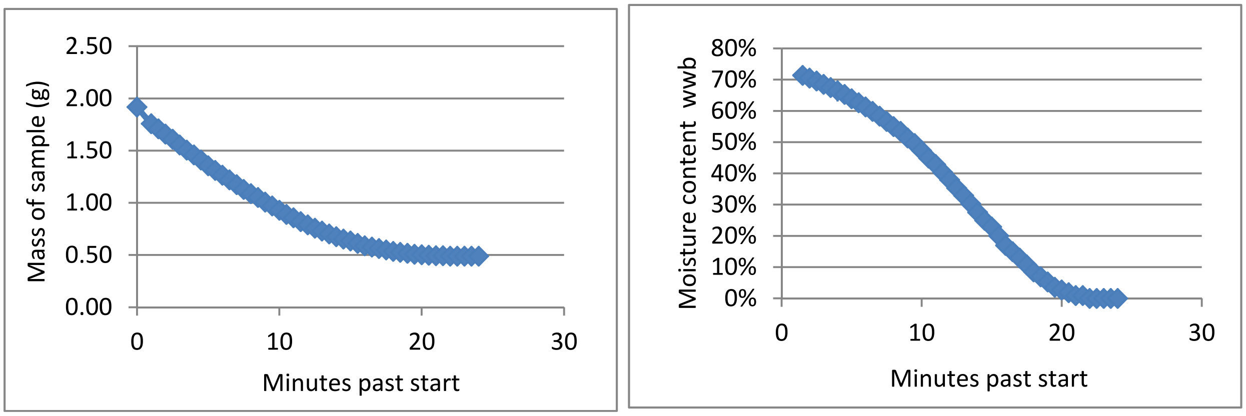

Figure 3. Single layer, 100°C, natural convection air drying of 2mm Crumbles particles. Left) Mass change rate. Right) Moisture content change rate.

Drying Experiments II: Forced Convection

The forced convection experiments were designed to determine drying rates when heat transfer and water vapor diffusion in the air adjacent to individual wood particles would not be limiting factors in the particle drying rate. Approximately 10g of wood particles were placed in a single layer (nominally) on a wire mesh screen where 100°C air flowed through them for a specified period of time. The particles were weighed at the beginning and end of the period to determine the average drying rate.

Apparatus and procedure

Using a lumped parameter heat and mass transfer model and Biot number estimation, we concluded that drying of a 2mm cubic wood particle would be limited by processes within the particle and not by diffusion rates in the air adjacent to the particle if the airflow around the particle exceeded 2 m/s. We additionally determined that the terminal velocity of wet 2mm Crumbles particles is approximately (and coincidentally) also 2m/s. Therefore, we chose to design and use a downdraft device so that the airflow forced the particles against a mesh screen.

The apparatus (Figure 4, left) consisted of a 124mm ID steel tube with two fans mounted in series at the top and separated by a single 60mm long baffle, a 75mm long baffle directly below the lower fan followed by 80mm of unobstructed flow within the tube, and a wire mesh basket[9] base to support the particles and the air handling apparatus (Figure 4, right). The 75 mm long baffle was necessary to prevent air from swirling the particles and forming non-uniform piles with highly variable airflow through the sample. The overall size of the device was limited by the internal height (0.398m) of the oven.

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[9] Square mesh opening, 2.1mm diagonal

Figure 4. Left) Forced air drying apparatus. Right) Dispersion of 10g (wet) 2mm Crumbles particles for forced air drying experiment, ~ 3.3g of OD wood.

The two fans[10] mounted in series were independently powered using one DC power supply[11] each, having voltage and current limiting functions. This allowed independent control of each fan's operating speed. While the fans were not intended for use in 100°C ambient air, they adequately produced the needed airflows for the time periods required in the experiments. They were rated for loads up to 0.45amps at 12V but to maintain constant ~3.5 m/s airflow, even as the fans severely overheated, we limited the supplied power to approximately 7 volts x 0.1 amp for the upper fan and 11 volts x 0.2 amps for the lower fan.

Individual experimental observations consisted of preheating the oven and the apparatus to an equilibrium temperature of 100°C, weighing and arranging approximately 10g of wood particles in a single layer (nominally) on the wire mesh in the apparatus, placing the apparatus in the oven and subjecting the particles to a 3.5 m/s 100°C airflow for a predetermined time period, and again weighing the wood particles.

There thermal mass of the oven and apparatus were sufficient to maintain 100°C +/- 5°C throughout the test period.

Results of the Forced Convection Drying Experiment

The results of the forced convection drying experiments are summarized in Figure 5. A single starting sample of about 1kg of wood particles was used for each series shown. Each data point is an observation made by drawing and measuring one ~10g sub-sample and drying it with the apparatus described above for the time period indicated. The sub-sample was immediately

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[10] Cooler Master® 120mm DC electric computer cooling fans

[11] BK Precision DC Power Supply 1735

weighed and subsequently fully dried to determine its oven dry mass as well as the moisture content at the beginning and end of the drying period.

The air temperature remained at 100° +/-5° C and the airflow velocity at ~3.5 m/s throughout the drying period for all observations.

The 2mm Crumbles particles dried from about 60% MC to 5% MC in approximately 3 minutes. The drying time for the 6mm Crumbles particles was approximately 5 minutes. The 6mm sawn cubes dried in about 10 minutes.

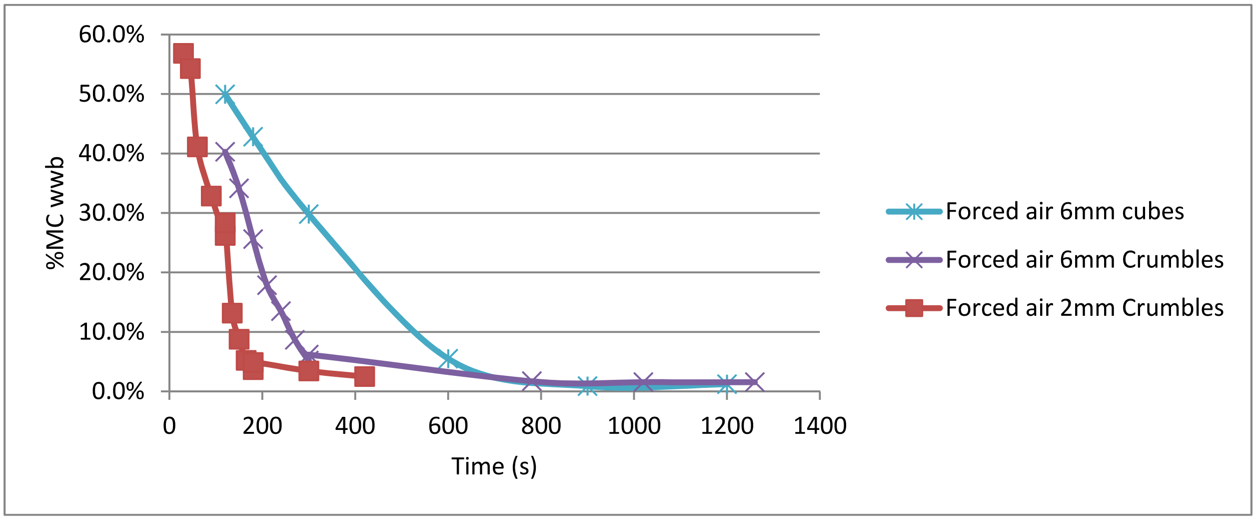

Figure 5. Forced air drying experiment results

Discussion

A variety of engineering schemes, ranging from low capital and low energy input passive systems to relatively high capital and high energy input actively controlled systems, are possible for drying manufactured small particle woody feedstock. However, the relative absence of engineering information that is needed to model heat and mass transfer in these particles leaves even “back of envelope” dryer design calculations wanting. To develop a basic level of understanding we observed an approximately 50mm deep layer of 2mm Crumbles drying in ambient air over several days and in an experiment essentially identical to the natural convection experiment described in this paper, we observed that a layer approximately 10mm thick dried at a rate requiring several hours to fully dry. In our experiment of heated natural convection drying in a one-particle deep layer, 2mm crumbles required about 20 minutes in a 100°C laboratory oven.

A shallow (nominally 1.5 particle deep) layer of 2mm Crumbles particles subjected to a 3.5 m/s airflow in a 100°C laboratory oven dried from about 60% MC to 5% MC in approximately 3 minutes. At 3.5 m/s we believe, based on a lumped parameter heat and mass transfer model, that heat and mass diffusion internal to the particle as opposed to the air surrounding the particle were limiting. Biot numbers for the particles were calculated using heat transfer coefficients and characteristic length estimates found in the wood handbook (Forest Products Laboratory 2010). In a similar experiment, but with 6mm Crumbles particles, we found that it took approximately 5 minutes to dry the larger particles.

To gain a sense of the difference between the checked surface Crumbles particles and a smoother surface particle of similar material, size and shape we repeated the forced convection experiment with identical conditions but using 6mm (nominal size) hand sawn cubes and found that the drying time was approximately doubled to about 10 minutes. At this time we attribute the difference primarily to the surface characteristics but recognize the need for a replicated study to rule out other sources of variance.

Figure 6 shows the declining moisture content as a function of time for the experiments reported here as well as the 10mm deep "pile."

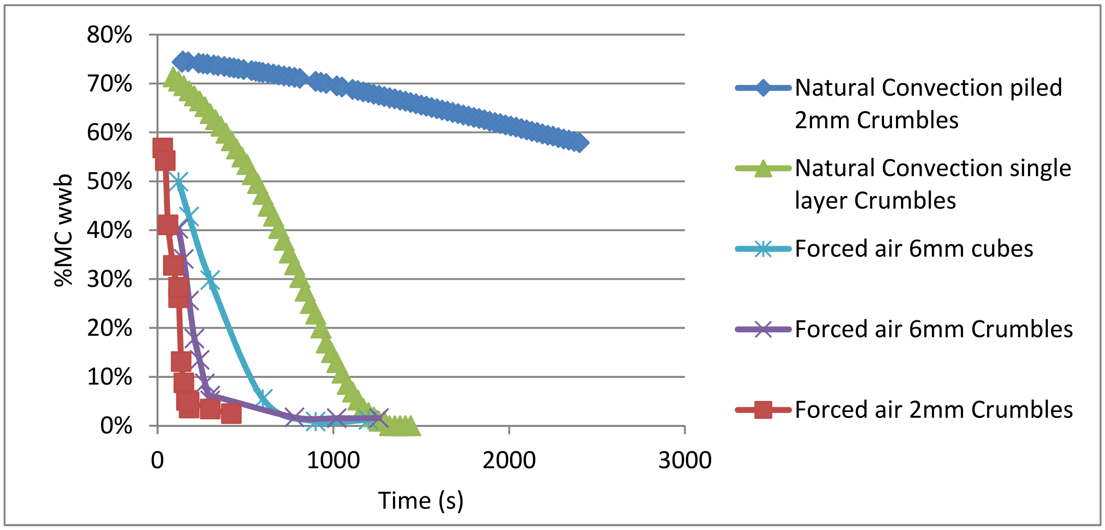

Figure 6. Summary of results

We did not choose to measure or control relative humidity (%Rh) in the preliminary experiments described here. But, since drying wood particles is a diffusion process that is ultimately driven by the difference in potential within the wood and its surroundings, the %Rh of the surrounding air is ultimately the primary dryer design and control parameter. Furthermore, since there are multiple design strategies for managing air temperature and humidity within a greater aim of optimizing energy consumption and capital costs, we believe that a well developed knowledge of the relationships between the wood particle and the air are necessary. For example, increasing the relative humidity of the surrounding air increases its heat transfer capacity to the wood particles. Dry air (low %Rh) has a relativity low heat capacitance of 1.0 kJ/kg•°C at 100°C. Increasing its water vapor content, adds an additional 2250 kJ per kg of water vapor in the drying air that can potentially be transferred to the wood particles. As of yet, we cannot adequately relate the rate of drying to the temperature and humidity of the surrounding air.

We checked that, in our experiments, the humidity of the oven air was not changing the drying rates over the duration of an experiment by examining the observed moisture content versus time for any diminishment in its rate of change before the wood moisture content reached 8% (bound water in cell the walls).

Conclusion

It is not well understood how much the physical properties of wood particles affect drying time and energy at low (100°C) temperature. From these brief experiments, several rules of thumb can be suggested:

- Airflow is sufficiently restricted within a pile or layer of wood particles to substantially affect moisture diffusion.
- Forcing air past and between the wood particles can greatly accelerate the drying rate.
- Biomass particles with high surface checking, and thus increased surface area to volume ratio (such as Crumbles particles), dry substantially faster than particles with less disrupted surfaces and a lower surface area to volume ratio.
- Smaller particles dry faster.
- Relative humidity may play a significant role in drying rate above some threshold.

The drying rate for a particle is determined by several limiting factors, none of which are sufficiently documented to populate a wood particle drying model:

- The rate of diffusion of water vapor within the particle.
- The rate of air diffusion within the particle.
- The rate of heat diffusion the wood.
- The rate of heat transfer to the wood from the adjacent air.
- The rate of water transfer from the wood surface to the adjacent air.

All are intrinsic properties of the particle except the rate of heat transfer to the wood from the air. Increasing the air velocity, thereby increasing the rate of convection, increases the rate of heat transfer to the wood for a given temperature differential. This set of constraints led to a second set of experiments aimed at determining the minimum drying time by having sufficient airflow over the particles such that convection rate did not limit the drying time.

These experiments addressed the time of drying, which is directly related to the capital expense of a dryer. Heat transfer was not specifically observed in these preliminary experiments. However we observed that a significant reduction in drying energy may be achieved by modifying surface properties of wood particles within a size class.

With funding through the Department of Energy Grant number (87366S12-I) Forest Concepts is continuing to research these hypothesis.

Acknowledgements

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