

Emissions from Biomass in a Rotary Dryer

Michael R. Milota

Abstract

Air emissions can be a limiting factor in obtaining the required permits to operate a plant when biomass is dried prior to further processing. Aged ponderosa pine, fresh ponderosa pine, Douglas-fir, and juniper were rotary dried to final moisture contents of 10 to 25 percent. The drum of the dryer was heated to temperatures of 200°C to 425°C. Total hydrocarbon emissions and the emission of various compounds were measured. While wood type strongly influenced emission levels, they were not strongly correlated with temperature or final moisture content. Total hydrocarbon emissions ranged from 0.10 to 0.25 g·kg⁻¹ of oven-dry biomass for aged material to 6.9 g·kg⁻¹ for fresh material. Ethanol emissions averaged 7,621 and 2,591 mg·kg⁻¹ for the fresh pine and the Douglas-fir, respectively, compared with less than 30 mg·kg⁻¹ for the aged material. Acetic acid emissions were also greatest for the fresh pine.

For many processes, such as combustion, torrefaction, and pellet manufacture, it is desirable to have the moisture content of biomass reduced. One disadvantage of predrying the material is the potential for emissions to the atmosphere from the wood. Some of these emissions are from volatile or semivolatile compounds present in the wood. An example of these is the terpenes that give pine a distinctive odor. Other emissions from wood are breakdown products from the heating process. Two-carbon compounds, such as ethanol, acetaldehyde, and acetic acid (Beall and Eickner 1970), can form when acetyl groups are released from the hemicellulose. Formaldehyde and methanol can come from methoxyl groups on the lignin. While the exact chemistry for emissions is complex, the total amount of compounds released tends to increase with temperature (Otwell et al. 2000, Banerjee 2001) and increase with greater change in moisture content (Milota 2006).

Total hydrocarbon emissions are usually measured by US Environmental Protection Agency (US EPA) Method 25A (Code of Federal Regulations 1991). The method utilizes a flame ionization detector (FID) to estimate the hydrocarbon concentration. The detector is calibrated to known standard gases, often propane in air. The FID method does not allow individual compounds to be identified. While simple, the method is not without pitfalls, such as moisture affecting the FID (Milota and Lavery 1999) and the FID response factors of the emitted compounds being unknown and different from the calibration gas.

Individual compounds are often measured by National Council for Air and Stream Improvement (NCASI) methods 99.01 or 105.01 (NCASI 2013). In these methods a gas sample is drawn through a cold aqueous solution, and water-soluble compounds are adsorbed into the water. The solution is then analyzed by gas chromatography. A

hazardous air pollutant (HAP) is a compound listed as such by the EPA. The wood industry is most interested in methanol, formaldehyde, acetaldehyde, propionaldehyde, acrolein, and phenol because these are listed HAPs and specified in the Plywood and Composite Panel Maximum Achievable Control Technology (MACT) rule. For purposes of the rule, these six compounds are measured and used as surrogates for all HAPs that might be present. While not HAPs and not listed in the MACT rule, ethanol and acetic acid are often of interest because of the amounts found in dryer exhaust.

The final category of pollutants is particulates. This could be dust or condensed hydrocarbons. EPA Method 5 is used to collect a sample onto filter paper, and the amount collected is weighed. In Oregon, the condensed hydrocarbons found in the impinger train may also be analyzed.

The goal of the present project was to determine the total hydrocarbon emissions and the emissions of the MACT HAPs, ethanol, and acetic acid from drying four types of biomass in a rotary dryer. The amount of emissions determine, in part, what type of control equipment is required in a facility, thus making emissions estimates vital to plant design and costing. This study is different from past work in that the biomass was typical of that from forest thinnings or treatments to reduce fire potential and contained wood, bark, and some dirt. In many processes,

The author is Professor, Wood Sci. and Engineering, Oregon State Univ., Corvallis (Mike.Milota@OregonState.edu [corresponding author]). This paper was received for publication in June 2013. Article no. 13-00052.

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such as pellet manufacture, the furnish must be cleaner and the amount of bark significantly less to make a suitable product. For other processes being developed, such as torrefaction, a lower-quality biomass is acceptable.

Materials and Methods

Biomass

Ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), and western juniper (*Juniperus occidentalis*) biomass samples were obtained with the assistance of an industrial partner. The biomass samples had been processed twice through a grinder at the time of collection to approximately 2-inch minus.

Two types of ponderosa pine were tested: aged and fresh. The aged ponderosa pine had been stored up to a year, was dark in color, had a musty odor, and contained a large fraction of fines. The starting moisture content ranged from 31 to 39 percent (all moisture contents are wet basis). The fresh ponderosa pine had a starting moisture content from 51 to 55 percent. The Douglas-fir was fresh with a starting moisture content from 46 to 52 percent. The juniper was aged, had a musty odor, and contained a large fraction of fines. The starting moisture content of the juniper was from 49 to 61 percent.

The wood material was delivered in plastic barrels and stored outdoors at 0°C to 15°C in the barrels until needed. All the barrels of a wood type were poured out onto clean concrete, mixed with a shovel, and returned to the barrels prior to experimentation to have the material more homogeneous among the drying runs within each wood type. Images of dried biomass are shown in Figure 1.

Drying

A small-scale rotary dryer that could handle biomass could not be procured. Smaller continuous rotary dryers that

were available for grain and finely ground material were unable to handle the irregular shape and stringy nature of biomass due to the size of the airlocks, feed screws, and the drum. Reducing the size of the biomass to fit the equipment would be likely to affect the emissions. We therefore modified an existing piece of equipment as described below so it could be used as a batch-type rotary dryer that could simulate the drying conditions typically found in industrial-scale biomass dryers.

The drying chamber (Fig. 2) consisted of a horizontal drum 90 cm in length and 55 cm in diameter. The drum had three lifting flights and rotated at 2 rpm. It was located inside of a larger drum. The air between the two drums was heated by a gas burner. The combustion gas did not contact the wood but remained outside the drying chamber.

Air was admitted into the drying chamber at a rate of 50 liters·min⁻¹ (at standard T and P). This was based on a calculation that indicated that 17 to 41 liters·min⁻¹ would be required to avoid saturated conditions and to remove 3.5 to 4 kg of water in 20 to 75 minutes. The air flow was set with a needle valve and measured with an MKS 1500 Series mass flow controller. The air line was heated to 120°C to prevent condensation on the air line. The air line (tube at center of photo in Fig. 2) discharged into the dryer toward the side of the chamber that did not contain wood on the lifting flights.

All air and water vapor left the dryer through a tube approximately 2 cm in diameter located at the center of the drying chamber. The entry to the tube was flared and covered with a cloth filter to prevent particles from entering. The sampling line for emissions was located inside of this tube and thus sampled the gas leaving the dryer.

The drying chamber was loaded with 9.09 kg of wet material. Drum rotation was started, and the heat was turned on. The temperature on the outside of the drum was controlled to 200°C, 315°C, or 425°C. It took approximately

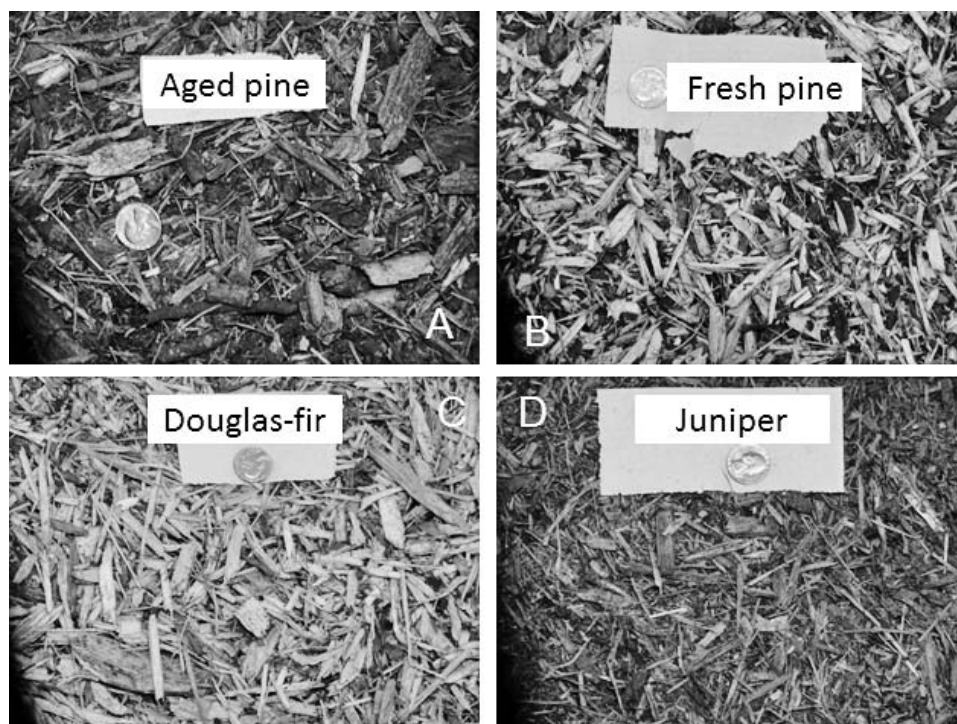


Figure 1.—Dried biomass: aged pine (A), fresh pine (B), Douglas-fir (C), and juniper (D).



Figure 2.—Inside of drying chamber. Air leaves through cloth filter at center and passes through 2-cm tube to back of photo. Air enters through small curved tube at center. Tube is concentric with exhaust tube.

1 to 2 minutes for the temperature to be reached at 200°C and 6 to 7 minutes at 425°C. Heat was applied to the outside of the drum for 10 to 80 minutes, after which the heat was turned off and drum rotation continued for another 7 minutes. During this time, the drying chamber temperature increased a little and then cooled. The end of drying was determined based on observed drying times and air temperatures in the drying chamber during previous experiments. The temperature of the air in the drying chamber reached 105°C to 155°C, depending on the type and moisture content of the material in the dryer and the set-point temperature. After drying, the outer drum and drying chamber were opened, and the material was removed and weighed. A 125- to 200-g sample was oven-dried (ASTM International 2007) so that the final moisture content, initial moisture content, and bone dry mass of biomass could be determined.

Three final moisture contents were targeted for each wood type and temperature: 10, 15, and 20 percent. One set of nine runs was done at 200°C and two sets (18 runs) at 425°C. At 315°C, the sample sizes varied: six runs for each type of pine and three for the other wood types. The actual final moisture contents ranged from 5 to 30 percent. Additional runs were done at some experimental conditions.

There was no humidity measurement for the exhaust air. It was assumed that the gas was saturated for the first part of the cycle while the evaporation rate was high and that after a selected dry-bulb temperature was reached, the air was no longer saturated. It was assumed that the wet-bulb temperature would remain constant and equal to the selected dry-bulb temperature for all greater dry-bulb temperatures. This selected temperature was determined by performing a mass balance on the water leaving in the exhaust and the weight loss from the biomass. The method produced consistent wet-bulb temperatures for each drum tempera-

ture: 86.7°C, 91.5°C, and 93.2°C for 200°C, 315°C, and 415°C, respectively. The wet-bulb temperatures at a given drum temperature were within 1°C among the wood types, and the aged pine with the lowest starting moisture content consistently had the lowest wet-bulb temperature.

The exhaust dry- and wet-bulb temperatures versus time were used to calculate the outlet humidity as a function of time. The inlet humidity (assumed to be 0.008 kg·kg⁻¹), outlet humidity, and the gas flow rate were used to calculate the rate at which water left the dryer. This, in turn, was used to calculate the moisture content of the biomass at any time during the drying cycle.

The heat transfer in a conventional rotary dryer is due mainly to convection from the hot gases to the wood. In the experimental dryer, however, the walls of the dryer drum were heated, and heat transfer occurred by conduction from the walls to the wood. The impact of the heat transfer mechanism on the total hydrocarbon and HAP emissions is not known.

Total hydrocarbon measurement

The sample was drawn from the dryer through heated lines (122°C, 127°C, and 130°C in three sections) to a heated dilution/filter box (134°C) where dilution air was added to the sample. The dilution air was heated and filtered house air supplied in a ratio to the sample of approximately four to one by volume to reduce the moisture content of the sample gas before it reached the analyzer. The exact dilution flow was measured using a bubble meter and verified by observing a reduction in the concentration of calibration gas. The sample line from the heated dilution/filter box to the analyzer was heated to 140°C. The three-way valve at the back of the analyzer was heated to 143°C. The entire sampling system was leak checked by closing the valve at the back of the analyzer, closing a valve at the dryer, and pulling a vacuum on the system.

The JUM VE7 hydrocarbon analyzer was calibrated using <0.1 ppm of air and EPA protocol gas (propane in air) at 99 and 609 ppm prior to each drying run. The calibration was checked at the end of each drying run. The fuel gas was hydrogen.

The hydrocarbon concentration reading from the analyzer is converted to a dry-basis concentration using the dilution ratio and psychrometric calculations based on the dry- and wet-bulb temperatures in the drum and then to a mass fraction of hydrocarbon using the atomic weight of carbon and a molecular weight of dry air. The amount of hydrocarbon leaving the dryer is determined from the amount of air leaving the dryer (measured with the MKS mass flow meter) and the mass fraction of hydrocarbon. This is divided by the mass of the biomass and expressed as unit emissions in grams of hydrocarbon “as carbon” per kilogram of bone dry biomass. The hydrocarbon value expressed in this manner is relative to the calibration gas and is not the actual mass emitted because the hydrocarbons leaving the dryer are an unknown mixture of compounds for which the FID response factors are not known.

Measurement of individual compounds

Sample collection.— A vacuum pump was used to draw dryer gas through the heated line to three midjet impingers connected in series and held in a glycol bath at -1°C. The first two each contained approximately 15 mL of BHA solution (benzylhydroxylamine in water, 30 g·liter⁻¹). The

BHA reacts with aldehydes to form oximes that are less volatile and more stable than the aldehydes. The third impinger was empty. The gas flow was controlled to 250 to 450 mL·min⁻¹ by a critical orifice. The flow through the impingers was measured before and after a drying run using a bubble meter. The ambient pressure and temperature were recorded at the beginning and end of each interval so the flow rates could be adjusted to standard conditions. The impinger connections were vacuum checked prior to each experiment, and the entire sampling system was vacuum checked weekly. After a run, the aqueous sample was weighed, and the impingers were rinsed with distilled water and hexane that were combined with the sample. Samples were stored in glass containers in the dark and refrigerated until laboratory analysis. The solution was later tested for methanol, ethanol, acetic acid, and phenol and the oximes of formaldehyde, acetaldehyde, propionaldehyde, and acrolein.

A second set of impingers containing deionized water was operated and handled in the same manner except that the hexane rinse was not done. The solution from these impingers was later analyzed for organic acids. The collection was in water because the BHA would have reacted with acids containing an aldehyde functional group.

Laboratory procedures.— The samples of BHA solution from the impingers were extracted three times with hexane in a separatory funnel to transfer the oximes in the hexane phase while the water-soluble compounds remained in the aqueous phase. The total hexane volume was approximately 20 mL. A 1-mL aliquot of each phase was transferred to an autosampler vial and spiked with an internal standard: nitrobenzene for the hexane phase and cyclohexanol for the aqueous phase.

A capillary gas chromatograph (GC) with a nitrogen phosphorous detector (NPD) was used for the hexane phase. The injector temperature was 200°C and the detector temperature 280°C. The injection volume was 1 µL. The column was a 105-m Restek RTX-5 capillary with a 0.25-mm outside diameter and a stationary-phase thickness of 0.25 µm. The oven schedule was 2 minutes at 120°C, 2°C·min⁻¹ ramp to 160°C, 40°C·min⁻¹ ramp to 220°C, and 6.5 minutes at 220°C. The column flow was 25 cm·s⁻¹, with 3 mL·min⁻¹ septum purge and a 1:10 split ratio with a glass wool-packed split injection liner. The detector makeup He was set to 20 mL·min⁻¹, and the H₂ was set to 3 mL·min⁻¹. The air was set to 140 mL·min⁻¹, and the source current was set to 2 pA.

The GC was equipped with a FID detector for the aqueous phase. The injector temperature was 175°C and the detector temperature 250°C. The injection volume was 1 µL. The column was a 60-m Restek Stabilwax capillary with a 0.53-mm outside diameter and a stationary-phase thickness of 1.5 µm. The oven schedule was 3 minutes at 60°C, 10°C·min⁻¹ ramp to 80°C, 3 minutes at 80°C, 10°C·min⁻¹ ramp to 230°C, and 10 minutes at 230°C. The column flow was 30 cm·s⁻¹, with 3 mL·min⁻¹ septum purge and a 1:10 split ratio with a glass wool-packed split injection liner. The detector makeup He was set to 25 mL·min⁻¹, and the H₂ was set to 50 mL·min⁻¹. The air was set to 500 mL·min⁻¹.

Samples collected in deionized water were sent to an outside laboratory for analysis by liquid chromatography (LC) for organic acids formic, pyruvic, DL-lactic, acetic, propionic, butyric, isovaleric, and valeric. The amount of a compound leaving the dryer is determined from a ratio of the gas flow through the impingers to the total gas flow

leaving the dryer. For example, if the gas flow through the impingers was 0.5 liter·min⁻¹ and the gas flow from the dryer was 50 liters·min⁻¹ and 0.1 mg was detected in the impinger, then 10 mg was emitted from the biomass. This is then divided by the mass of the biomass and expressed as unit emissions in milligrams of compound per kilogram of bone dry biomass.

An analysis of variance was done with the amount of total hydrocarbon or individual compound released as the dependent variable. The independent variables were wood type and drum temperature as main effects with final moisture content as a covariate.

Results

The initial moisture contents for the material had standard deviations of approximately 1 percent for the Douglas-fir and fresh pine and 2 percent for the aged pine and juniper. Even with fairly uniform initial moisture content among the experiments within a species, it was difficult to dry to the correct moisture content, especially for short drying times. Drying times (Table 1) ranged from 11 minutes for the aged pine at the highest temperature to over 60 minutes for the other wood types at the lowest temperature.

Total hydrocarbon

The total hydrocarbon emissions (reported “as carbon”) as a function of moisture content for each temperature are shown in Figure 3. The analysis of variance with wood type, drying temperature, and final moisture content showed that only wood type significantly ($P = 0.00$) affected total hydrocarbon emissions. Clearly, the aged pine and juniper (also aged) had far lower total hydrocarbon emissions than the fresh Douglas-fir and fresh pine. The aged materials had been ground and then stored for up to a year, during which time both the moisture content was reduced and volatile compounds escaped from the wood. The total hydrocarbon emissions from fresh pine and Douglas-fir were significantly different from each other, but it could not be shown that the emissions from aged pine and juniper were different from each other.

There appears to be a slight tendency among the runs for the total hydrocarbon emissions to be greater when the final moisture content is lower (Fig. 3); however, this was not statistically significant based on the regression coefficients in the figure and the analysis of variance ($P = 0.09$). Figure 3 shows data from different runs. The only data set that has a positive slope (0.05 g·kg⁻¹·%⁻¹ with $r^2 = 0.11$) is Douglas-fir at 425°C. We attribute this mostly to the data point representing the wood dried to 11.2 percent moisture content with 1.47 g·kg⁻¹ of emitted hydrocarbon. We could find no reason to delete this point from the data set even

Table 1.—Average drying times for all experiments.

Wood type	Initial moisture content (% wet basis)	Drying times (min) at each temp. ^a		
		200°C	315°C	425°C
Aged pine	32.6	35.3	16.5	11.1
Fresh pine	51.9	69.0	38.6	27.1
Douglas-fir	46.1	64.7	32.4	21.4
Juniper	55.5	65.0	39.3	24.1

^a Each value represents from two to eight experimental runs. Times do not include the 7-minute cool down.

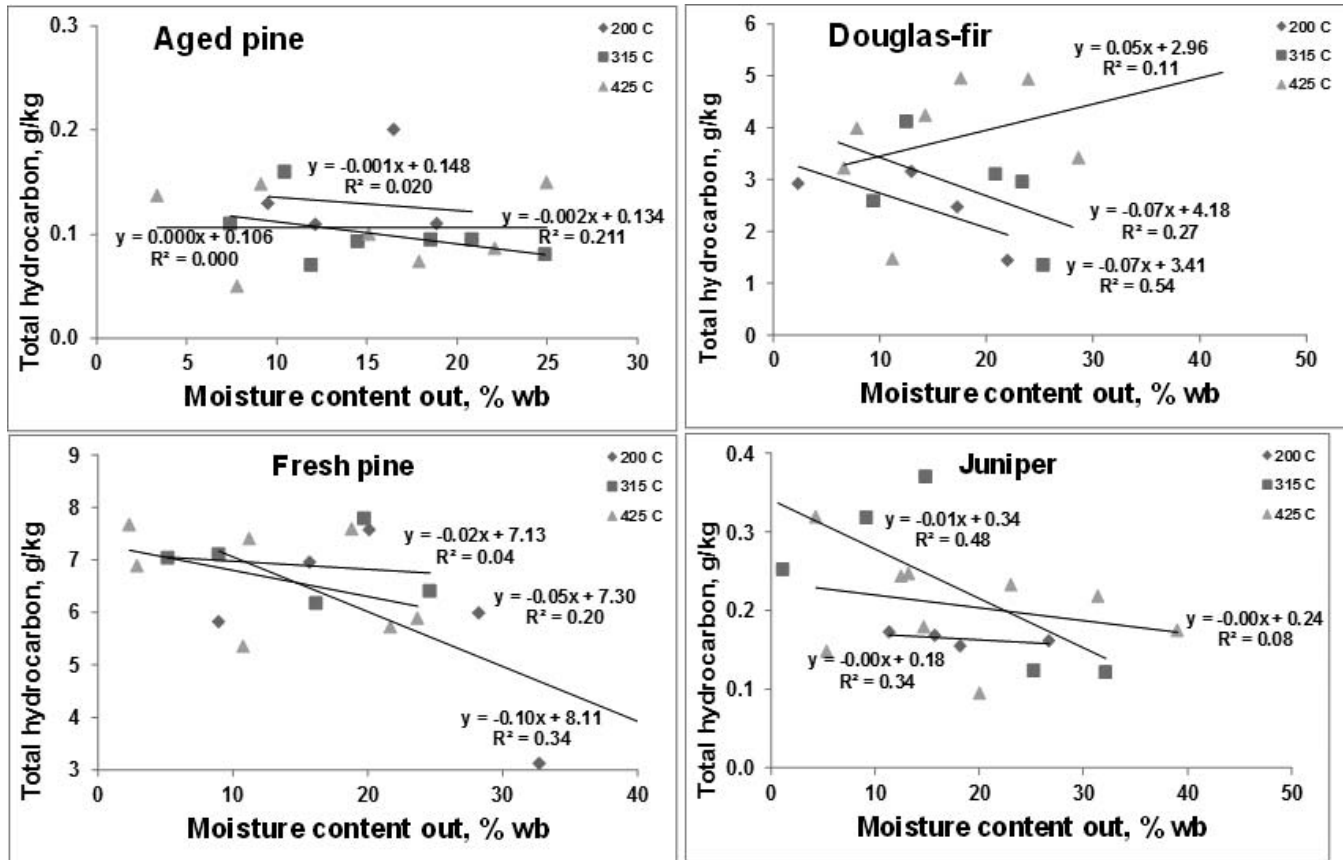


Figure 3.—The total hydrocarbon emissions as a function of moisture content and temperature.

though it appears to be an anomaly. Without this data point, the slope is $0.02 \text{ g}\cdot\text{kg}^{-1}\cdot\%^{-1}$ with and $r^2 = 0.06$. Within any one run, the hydrocarbon emissions increase as moisture content decreases (Fig. 4). The rate of emissions for fresh biomass is greatest during the first part of drying, then much less later in the process, as depicted by the slope of the lines. For the example shown, fresh pine dried at 425°C showed a release of about 88 percent of the total hydrocarbon emissions from green to 25 percent moisture content. This is consistent with Banerjee (2001), who states that “there is an initial burst of pinene very early in the process.” Graphs presented in McDonald et al. (2002) also support this. The

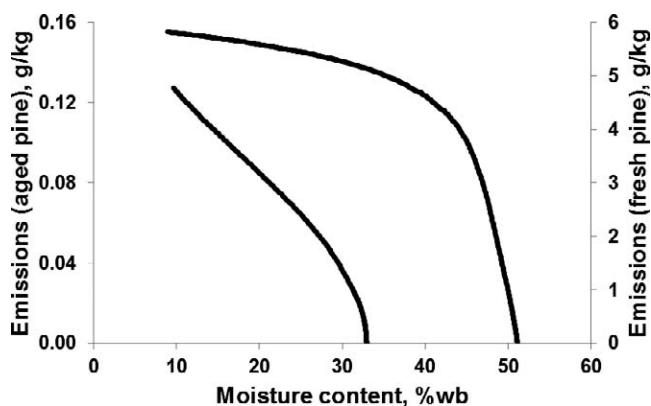


Figure 4.—Total hydrocarbon emissions as a function of biomass moisture content for aged pine and fresh pine dried at 200°C . Each line represents one drying run.

total hydrocarbon emissions from Douglas-fir follow the same pattern. Thus, the exact final moisture content may not be an important consideration when estimating the drying emissions for fresh biomass. The shape of the curve was more linear throughout drying for the aged biomass, so final moisture content may be a more important consideration. For the aged pine in Figure 4, only 50 percent of the total hydrocarbon emissions occur above 25 percent moisture content. However, the total hydrocarbon emission level was very low. The total hydrocarbon emissions from juniper followed the same pattern.

Temperature of the dryer did not have a statistically significant effect on the total hydrocarbon emissions ($P = 0.13$). This might be explained if most of the hydrocarbon emissions are due to material already present in the biomass rather than biomass breakdown. This might be the case in this work because the final moisture content was not low, 10 to 25 percent wet basis, and the wood temperature remains well below the set-point temperature due to evaporation. A lack of relationship between total hydrocarbon and temperature was also reported by Ingram et al. (2000) for southern pine lumber. They reported 5.85 and $5.93 \text{ lb}\cdot\text{mbf}^{-1}$ (approximately 1.40 and $1.42 \text{ kg}\cdot\text{m}^{-3}$) emitted at high and conventional temperature, respectively.

A facility could dry $14,300 \text{ bone dry t}\cdot\text{y}^{-1}$ ($1,298,000 \text{ kg}\cdot\text{y}^{-1}$) of the fresh pine before reaching the Title 5 threshold of $100 \text{ t}\cdot\text{y}^{-1}$ ($90.9 \text{ Mg}\cdot\text{y}^{-1}$) based on VOC emissions. Title 5 of the Clean Air Act Amendments of 1990 stipulates that facilities exceeding this threshold are major sources and are subject to more extensive permitting and reporting requirements and may be required to install additional emissions

control equipment (US EPA 2013). Reaching the threshold is based on all VOC emissions from the facility; however, the dryer is often the greatest contributor to a site's emissions. The facility could dry far more of the aged pine or juniper, and the VOC emissions would probably not reach the threshold. The results presented cannot be extended to fresh juniper.

Individual compounds

The unit emissions of compounds are shown in Tables 2 and 3. Each value for the HAP compounds (Table 2) represents the average of two to six drying experiments to final moisture contents of 10 to 25 percent. The standard deviations for replications with low values are on the same order as the mean. The larger values have standard deviations that are 20 to 40 percent of the mean. Phenol was not detected in any sample and is omitted from the table.

The samples analyzed for organic acids (Table 3) by LC represent the average of two values. Differences between replicate samples ranged from a 57 percent average for aged pine at 315°C to 168 percent for juniper. For juniper, isovaleric acid was detected in the second replicate but not the first, while valeric acid was detected in the first but not the second. Similar to the values determined from NCASI (1999), there was considerable variability in the results.

Propionic acid was not detected in any sample and is omitted from the table.

An analysis of variance with wood type and drying temperature as independent factors and moisture content after drying as a covariant showed that wood type was a significant factor ($P = 0.00$ to 0.04 , depending on the compound) affecting the emissions of each compound except propionaldehyde ($P = 0.72$). As with total hydrocarbon, the fresh material generally has higher emissions than the aged material, although a true comparison can be made only for the pine. Ethanol and methanol, in particular, are much higher for the pine and somewhat higher for the Douglas-fir than the aged biomass ($P = 0.00$ for both). The fresher biomass also had higher acetaldehyde emissions ($P = 0.00$). Juniper had higher formaldehyde emissions ($P = 0.04$) than the other wood types.

The scatter in the data tends to hide any relationship of the amounts emitted with final moisture content. This was a statistically significant factor only for methanol, formaldehyde, acetaldehyde, and acrolein. Obviously, the amount emitted should increase as moisture content gets lower; however, the impinger technique yields one value for each compound for a drying cycle, and a chart similar to Figure 4 cannot be constructed. McDonald et al. (2002) present data showing that methanol, ethanol, and formaldehyde (but not

Table 2.—Average emissions for hazardous air pollutants.^a

	Temp. (°C)	Avg. emissions (mg·kg ⁻¹ of bone dry biomass)				
		Formaldehyde	Acetaldehyde	Propionaldehyde	Acrolein	Methanol
Aged pine	200	3.19	16.3	3.27	0.65	24.4
	315	1.25	7.1	0.39	0.68	30.8
	425	5.67	16.9	1.09	1.34	43.8
Fresh pine	200	1.69	66.3	1.85	1.00	244
	315	2.61	78.7	0.78	1.56	203
	425	15.46	80.6	1.00	2.89	252
Douglas-fir	200	9.58	75.7	1.35	0.86	113
	315	1.89	52.9	0.78	0.94	99
	425	5.62	46.1	0.60	1.43	136
Juniper	200	8.49	6.5	0.41	1.07	24.9
	315	13.22	15.9	0.94	1.67	64.8
	425	14.87	21.9	0.93	1.98	65.9

^a Phenol was tested for but not detected.

Table 3.—Average emissions for nonhazardous air pollutant compounds.^a

	Temp. (°C)	Avg. emissions (mg·kg ⁻¹ of bone dry biomass)								
		Ethanol	Formic acid	Acetic acid (GC)	Acetic acid (LC)	Pyruvic acid	DL-Lactic acid	Butyric acid	Isovaleric acid	Valeric acid
Aged pine	200	25.2		37.0						
	315	28.9	5.5	25.4	11.9	0.0	0.0	0.0	0.0	0.0
	425	16.2	33.3	42.8	34.9	0.0	1.6	4.5	126.3	0.0
Fresh pine	200	8,676		237						
	315	7,600	30.0	234	202.6	0.0	13.1	38.6	0.0	0.0
	425	6,589	88.6	246	374.8	3.9	18.6	341.4	320.3	0.0
Douglas-fir	200	2,747		46.2						
	315	2,048		56.4						
	425	2,979	18.6	80.5	52.6	0.0	0.0	22.3	35.3	26.0
Juniper	200	1.4		30.7						
	315	0.4		32.7						
	425	1.4	12.8	33.5	50.2	0.0	0.0	8.9	5.2	30.6

^a Propionic acid was tested for but not detected. Missing values indicate that no sample was taken. GC = gas chromatography; LC = liquid chromatography.

acetaldehyde) follow a pattern with moisture content similar to the hydrocarbon in the present study.

The acrolein emitted increased with temperature ($P = 0.04$); however, clear relationships with temperature are lacking for the other compounds ($P = 0.07$ to 0.85). Acrolein would be expected to increase with temperature and is often a product of combustion, as in cigarette smoke. Methanol and formaldehyde would be expected to increase with temperature based on past studies. Past studies indicate that acetaldehyde probably decreases with temperature. There is a lack of information on trends with temperature for the other compounds. The sum of the HAP emissions was greatest at 425°C for three of the four wood types.

The emission amounts were estimated prior to starting this project based on data (NCASI 1999) for a rotary dryer drying particleboard furnish (cleaner and less bark than study material). The estimated emissions were methanol 21, formaldehyde 60, acetaldehyde 14, propionaldehyde 1, and acrolein $3\text{ mg}\cdot\text{kg}^{-1}$. The emissions in the present study were both higher and lower, depending on the compound, wood type, and temperature.

There is a trend for the organic acid emissions to increase with temperature. The presence of the five-carbon acids may suggest depolymerization of carbohydrates. McDonald et al. (2002) reported valeraldehyde in the emissions from radiata pine lumber.

The total hydrocarbon emissions are less than the sum of the individual compounds for three reasons. First, most of the compounds are oxygenated and have an FID response that is less than propane. Methanol, for example, would appear as approximately 6 ppm if the actual concentration were 10 ppm. The second factor is caused by reporting as carbon. A molecular weight of 36 (three carbons) is used to convert the analyzer concentration to a mass (instead of 44, the actual molecular weight of the propane calibration gas). The final factor is the presence of moisture, which depresses the FID reading. This effect was minimized by diluting the gas sample to approximately 10 percent moisture before it reached the FID.

The HAP emissions may be a consideration in whether a plant drying these types of biomass reaches the Title 5 emission thresholds of $10\text{ t}\cdot\text{y}^{-1}$ ($9.1\text{ Mg}\cdot\text{y}^{-1}$) of any one HAP or $25\text{ t}\cdot\text{y}^{-1}$ ($22.7\text{ Mg}\cdot\text{y}^{-1}$) of combined HAP emissions. Ethanol is not classified as a HAP, so methanol is the major HAP emitted. For the emission of $250\text{ mg}\cdot\text{kg}^{-1}$ ($0.50\text{ lb}\cdot\text{t}^{-1}$) of methanol, a facility could dry 40,000 bone dry tons (36,400 kg) annually before reaching 10 tons of methanol released annually. Again, this is based only on the dryer. In practice, all site methanol emissions would contribute to the $10\text{ t}\cdot\text{y}^{-1}$ limit. Because methanol constitutes more than half the total HAP emissions, the $10\text{ t}\cdot\text{y}^{-1}$ threshold would be reached before the combined $25\text{ t}\cdot\text{y}^{-1}$ threshold. A plant might also trigger Title 5 due to total hydrocarbon emissions, as discussed above.

Conclusions

All results were obtained by heating the outside of the drum containing the woody material. Heat is introduced during commercial rotary drying by blowing hot air into the drum. The particles in the experimental dryer contacted a steel surface that was hotter (200°C to 425°C) than the air temperature in the dryer (105°C to 155°C). The effect of this

when comparing the results with conventional rotary drying is not known.

The total hydrocarbon levels are much higher for the fresh biomass compared with the aged material. This suggests that much of the total hydrocarbon emissions are from extractive compounds present in the wood. These compounds have had a chance to volatilize from the aged material between the times of harvesting and drying. The fresh pine had the highest level of total hydrocarbon emissions followed by Douglas-fir, which was also fresh.

The total hydrocarbon emissions did not vary much with final moisture content within a wood type. This is because nearly all of the emissions occur above 30 percent moisture content for Douglas-fir and fresh pine, and further drying to 20 or 10 percent has only a small effect. For the other wood types, the total hydrocarbon emissions are more uniform with time and much lower. Data from within a run (such as shown in Fig. 4) would suggest that only 10 to 20 percent of the total hydrocarbon emissions occur below 20 percent moisture content. Dryer temperature did not strongly affect the total hydrocarbon emissions, and any small effect is masked by the amount of scatter in the data.

With the exception of formaldehyde emissions from the aged juniper, HAP emissions were typically higher in the fresher material. Total HAP emissions did not exhibit clear trends with temperature, although they were greater at 425°C compared to 200°C for three of the four wood types. Similarly, there were not strong trends between the HAPs produced and final wood moisture content. Ethanol (not a HAP) is a major component of the emissions from the fresh pine and Douglas-fir. The five-carbon acid isovaleric was detected for drying at higher temperatures.

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