

REDUCTION OF ORGANIC EMISSIONS BY USING A MULTISTAGE DRYING SYSTEM FOR WOOD-BASED BIOMASSES

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ABSTRACT

Organic emissions during the thermal drying process are strongly dependent on the drying temperature. In the traditional single stage drying system, the inlet temperature of the drying air has to be relatively high in order to keep the airflow for drying small. In the multistage drying system, the drying airflow is heated up again after the first drying stage with higher moisture content, and then again after the second, and subsequent drying stages. In this method, the drying temperatures are limited in all stages to acceptable low levels, and only the moisture content of the drying air is increasing from one stage to another. As a result the multistage drying system has a lower drying temperature. We have studied the dependence of the organic emissions on the drying temperature, and present the results from drying units operating at temperatures of 100-200 °C and below 100 °C. The results are compared to previous measurements found in the literature. The estimates for the emissions at higher drying temperatures are derived from the literature values.

INTRODUCTION

Drying of wet biofuel before combustion homogenises the fuel and this produces certain advantages for the combustion process (Tillman et al., 1981). The unburned organics (both gaseous and particles) and the CO emissions in the flue gases signify the disturbed and imperfect combustion of fuels (Edwards, 1974; Warman, 1983;

Olsson and Persson, 1991; Raunemaa et al., 1999; Cicciooli et al., 2001). The homogenisation of biofuels before combustion reduces these emissions (Tillman et al., 1981; Wimmerstedt, 1999). The instant drying and combustion of moist biofuels also helps to avoid long storage times. Although the effective heating value of biomass may not deteriorate much as a result of dry-matter losses during storage times extending to several months, the handling of moist biomass does become difficult due to the growth of micro-organisms (Kofman et al., 1999). This may introduce severe problems not only in the field storage and transport, but also in the power plant's storage rooms of biomass (Kofman et al., 1999).

The moist biomasses are effectively dried before combustion in flue gas and steam dryers; this causes, however, certain environmental and operational risks (Tapanainen, 1982; Wimmerstedt, 1999). The environmental risks of air and flue gas dryers, which operate with inlet air or flue gas temperatures of 150-200 °C, are associated with a strong smell and ozone formations (Setzman et al., 1993; Wastney, 1994; Bridgewater et al., 1995; Cicciooli et al., 2001). This is due to emissions of gaseous organic compounds (mainly all classes of terpenes) into the atmosphere (Lavery and Milota, 2001; Danielsson and Rasmusson, 2002). In addition to these emissions, steam dryers produce high quantities of organically loaded condensed water flows (Wimmerstedt, 1999).

The operational disturbances of different dryer technologies are associated with the emissions of tacky lipids (Fagernäs, 1992). Tacky lipids, which consist mainly of fatty and resin acids, are considered to be potential precursors to the deposits found on the surfaces of peat and bark dryers (Fagernäs, 1992). It is possible to reduce the emissions of lipids from bark by avoiding lipid-rich substances, and by storing the bark before drying (Fagernäs, 1993). The deposits can be removed from the drying equipment by washing with alkaline wash liquids or, mechanically, by using a chisel (Fagernäs, 1993).

The application of a multistage drying system (MSDS) is proposed to decrease the environmental and operational problems met earlier in using other drying technologies. This paper describes the influence on the operability of MSDS of the organic emissions from wood-based biomass drying, and considers their environmental effects in combined heat and power (CHP) plants. The maintenance of the MSDS in terms of its operability requires the choice of maximum drying air inlet temperatures and moisture reductions in wood in the drying stages. The work is based on the emission measurements from continuously operating fixed-bed wood dryer. Hard- and softwoods, bark, chips and logging residues are all of equal importance.

THE MULTISTAGE DRYING SYSTEM

In the multistage drying system, the drying air with higher moisture content after the first drying stage is heated up again, and then again in subsequent drying stage. As a result the MSDS requires a lower the inlet temperature of the drying air, because of increased water absorbing capacity of the drying air due to consecutive drying steps (Spets, 2001). The principal layout of the MSDS is presented in Figure 1. By assuming an equal mass flow rate, the greater the number of drying stages in the MSDS, the lower the drying air temperature (T_1) in each drying stage to produce an equal moisture change ($x-x_0$) in the drying air to that in a one stage drying system having a higher drying air temperature (T_2).

A scheme illustrating the principle for integrating the steam boiler and MSDS in a CHP plant is shown in Figure 2. The moist wood is heated and partly dried in the first drying stage to temperatures of 70-80 °C by low temperature process secondary heat flows. The exhaust air from the first drying stage can be out-purged into the atmosphere, if the organic emissions from wood drying in temperatures below 100 °C are not significant. The wood is fed from the first drying stage to the second drying stage (i.e. into the first drying stage of the closed multistage structure) with preheated drying air. The highest feed temperatures of the drying air in closed multistage structure depend on the temperatures of back-pressure and extraction steams (in the temperature range of 130 to 200 °C).

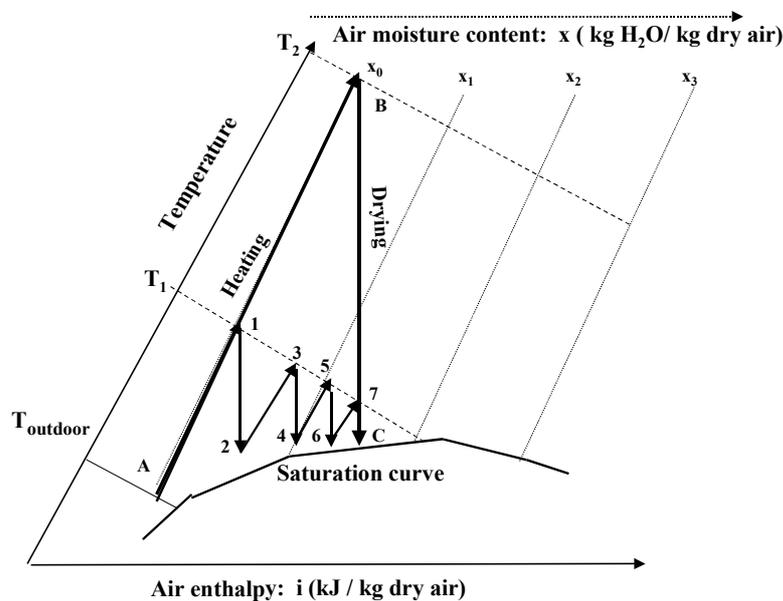


Figure 1. Comparison of one stage (A-B-C) and multistage drying systems (A-1-2- ... -C) with equal drying air flow rates but different drying air temperatures ($T_1 < T_2$). The Mollier (i,x)-diagram used for the illustration is Salin-Soininen perspective

transformation. The MSDS is a closed structure without drying air out-purge between drying stages. (Spets, 2001).

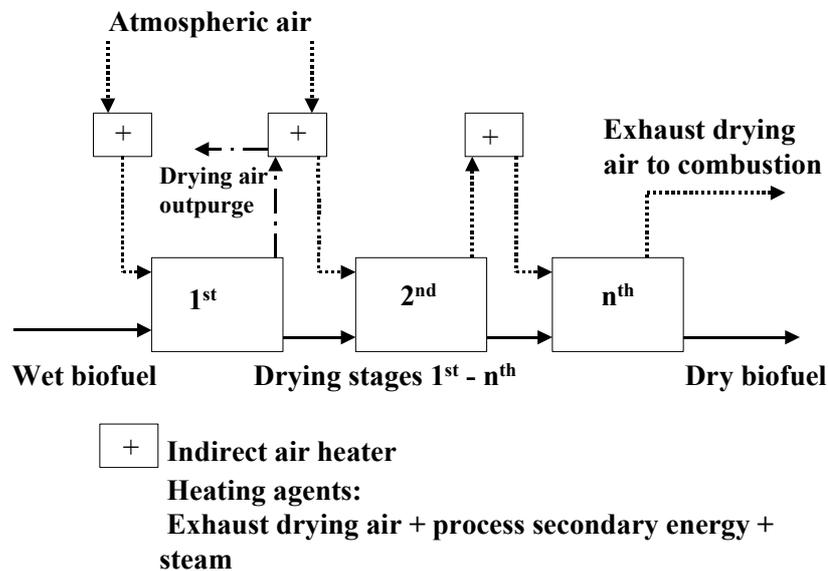


Figure 2. Biofuel multistage drying system in a CHP boiler plant using different drying air heating sources. Drying stages of 2nd to nth form a closed MSDS structure without drying air out-purge between drying stages. (Spets and Ahtila, 2001, USA and Norway; Spets and Ahtila, 2002).

It can be seen from Figure 2 that heat recovery from the exhaust air of the first drying stage can be accomplished to heat the air flow into the second drying stage; this decreases the steam demand for drying air preheating (Spets and Ahtila, 2002). The exhaust drying air from the last drying stage can be fed through a cooling and vapour condensing unit before mixing with the combustion air inlet. Different feed drying air temperatures in each of the drying stages in the MSDS enable effective utilization of low temperature process secondary heat flows in drying. As a result, the energy efficiency of CHP plants increases, while at the same time the emissions are reduced. The MSDS provides solutions in integrated pulp and paper mills, in which there are high quantities of wood residues from pulp and paper making processes, and heating sources of different temperature levels available.

Moisture content sets limitations in wood drying. The drying is stopped at fiber saturation point (FSP), which is the moisture content below which all remaining water in wood is increasingly tightly bound (Siau, 1984). A calculation of wood FSP gives a value of 0.28 kg H₂O/ kg dry solids (Siau, 1984). If the drying action continues below FSP, the drying starts to consume excessive energy for heating wood and losing the bound water (Wastney, 1994). Also the drying time of wood increases (Spets and Ahtila, 2001, USA).

Potentials of MSDS in CHP

The installation of the MSDS increases the power-to-heat ratio of the CHP plant as compared to a CHP plant without MSDS installation (Spets and Ahtila, 2002). In a focused wood and peat combusting CHP boiler plant, an calculated increase of nearly 8 % is possible in power production when the dry solids capacity is not increased after MSDS installation (Spets and Ahtila, 2001, USA and Norway). Simultaneous increases in both output power and output heat values are possible when the MSDS contains the partial out-purge of exhaust drying air into the atmosphere and/or when the exhaust drying air cooling and water condensing unit enables an increase in the capacity of the CHP plant boiler (Spets and Ahtila, 2001, USA and Norway; Spets and Ahtila, 2002). The flue gas mass flow from the combustor can be reduced after the moist exhaust drying air out-purge into the atmosphere (Spets and Ahtila, 2002). Depending on the structure of the MSDS, the exhaust drying air-cooling and water vapour condensing unit enables heat recovery of 30-50 % at lower temperature level of the total drying heat consumption in the MSDS (Spets and Ahtila, 2002). If no drying air partial out-purge or vapour condensing unit is used, all exhaust drying air from the MSDS can be fed into the combustion.

CONSIDERATION OF ORGANIC EMISSIONS FROM WOOD THERMAL DRYING

The organic emissions from wood drying at temperatures under 200 °C are composed of lipophilic extractives (Fagernäs and Sipilä, 1996). At temperatures over 200 °C, the emissions contain considerable amounts of hydrophilic extractives and compounds from the thermal degradation of wood solids (Fagernäs and Sipilä, 1996). The organic emissions from biomass dryers into the environment include carry-over particles, gaseous volatile organic compounds and organic compounds in condensed water. In Table 1, the amounts of extractives in the dry solids of different wood species and in their barks are shown (Fengel and Wegener, 1984; Sjöstrom and Alén, 1999). From these it can be estimated that especially bark drying may release high quantities of organics into the atmosphere.

Table 1. Extractives [wt-% in dry solids] in different wood species and in barks.

Wood species	Extractives [wt-% in dry solids]
Softwood (i.e. conifers)	2 – 5 ^a
Hardwood (i.e. broad-leaved trees)	2 – 4 ^a
Bark	20 ^b
^a Average values of typical common pulpwood species. Different wet chemistry analysis methods were used (Sjöström and Alén, 1999). ^b Order of magnitude for analyses of some European spruce and pine barks. Extraction sequences of ether, ethanol and hot water were used (Fengel and Wegener, 1984).	

In the following, detailed data from a literature survey are listed; these concern emission characteristics of both volatile organic compounds and condensing volatile organic compounds from wood drying.

VOC emissions from wood drying

VOC emissions from wood drying are principally strong smelling terpenes, of which monoterpenes as α - and β -pinenes are the major components (Cronn et al., 1983; Wastney, 1994; Bridgewater et al., 1995; Lavery and Milota, 2001; Danielsson and Rasmuson, 2002). An emission value of 75 % of total terpene content for chipped forest wood fuels (Nordic pine and spruce) is given for both direct flue gas dryers and indirect dryers (i.e. steam dryers) (Setzman 1993; Nyrén, 1992). VOC emissions from softwood and hardwood drying are reported to differ from each other both qualitatively and quantitatively, while softwood drying releases higher quantities of VOCs than hardwood drying (Otwell et al., 2000; Banerjee et al., 1998). VOCs from hardwood drying are mainly degradation products from the thermal degradation of wood, whereas most VOCs from softwood drying are terpenes (Otwell et al., 2000; Banerjee et al., 1998). The VOCs from both hard- and softwoods dryings include methanol and formaldehyde, both of which are regarded as hazardous air pollutants (Cronn et al., 1983; Otwell et al., 2000). There are differences between terpene concentrations in different parts of one wood species, and these differences influence wood drying emissions (Setzman et al., 1993). In spruce, for example, the terpene concentration in wood is 1-2 kg terpenes / ton dry solids, while fresh knots of spruce contain 10-15 kg terpenes/ ton dry solid (Setzman et al., 1993). It is also noticed from lumber drying that much greater amounts of terpenes are found in heartwood than in sapwood (Ingram et al., 2000).

Organic load in condensed water from wood drying

VOCs, which are condensed in exhaust drying air-cooling, consist of components such as fatty acids, resin acids, diterpenes and triterpenes (Bridgewater et al., 1995). The tacky lipids, which consist mainly of fatty and resin acids, may occur in the exhaust drying air flow in the vapour phase, or in the liquid phase as aerosols, or as enriched on the surface of carry-over particles (Wastney, 1994; Bridgewater et al., 1995). The smallest aerosol particle diameter, the number of aerosols and their particle size distribution depend on air temperature, and on the degree of air supersaturation (i.e. moisture content in relation to the saturated state) (Wastney, 1994; Banerjee et al., 1995).

The appearance of organic compounds in condensates from steam drying has been studied and reported (Fagernäs, 1992; Fagernäs, 1993). The results of such studies can be scaled in estimating the amount of condensed water from wood drying with air by considering the influence of drying air inlet temperatures on organic emissions. The results obtained in laboratory scale tests of pine bark in a steam dryer are shown in Table 2 as a function of drying temperature. Chemical oxygen demand (COD) values of condensates from different dryers of wood-based biomasses are reported to vary within the range of 600 to 2900 mg/dm³ (Fagernäs and Sipilä, 1996). Corresponding pH values of the condensates are reported to vary between 3.3 and 7.5 (Fagernäs and Sipilä, 1996).

Table 2. Amounts of organic emissions released from pine bark drying with short delay times in laboratory-scale steam dryer (Fagernäs, 1992; Fagernäs, 1993).

Temperature range [°C]	Emission [g organics/ kg dry solids]
150-200	≈ 1
250-300	≈ 40
300-350	≈ 110

The organic compounds in condensed water from bark drying are reported to be mainly less water-soluble or totally water-insoluble organic compounds such as high-molecular-mass carboxylic acids ($\text{CH}_3\text{-(CH}_2\text{)}_n\text{-COOH}$, $n=10\text{-}30$) and resin acids (Fagernäs, 1992; Fagernäs, 1993; Westermark, 1996). Water-insoluble organic compounds are found to condense in water if the condensation temperature is low enough (Westermark, 1996; NCASI, 1983). The water-soluble organic compounds that were identified and mentioned were low-molecular-mass carboxylic acids, aliphatic aldehydes and aliphatic alcohols (Fagernäs, 1992; Fagernäs, 1993; Westermark, 1996).

Emission mechanisms

It is important to know the mechanisms that influence the formation of emissions of organic compounds in wood drying. The basic emission mechanisms are direct evaporation (i.e. vapour pressure of pure components increases as the temperature increases), steam distillation and thermal degradation (Wastney, 1994). The volatile organic compounds, which are released from wood in thermal drying, are released as a consequence of the gradual heating of wood dry solids.

Many organic compounds have relatively low vapour pressures at drying temperatures of up to 180-220 °C to evaporate directly as their own fraction, but they do, however, evaporate because of steam distillation (Wastney, 1994). In steam distillation, the evaporation occurs when the sum of the partial vapour pressure of the individual organic compound and water is greater than the existing total pressure (Wastney, 1994).

In thermal degradation, the solid matter degrades, when high-molecular-mass organic compounds split into lower molecular-mass organic compounds in increasing temperature (Fengel and Wegener, 1984; Münter and Bäcker, 1992). Thermal degradation starts at temperatures of 100-150 °C and increases as the temperature rises (Fengel and Wegener, 1984; Nyrén, 1992). In temperatures of up to around 200 °C wood thermal degradation is reported to occur mainly on the outer surface of wood particle (Nyrén, 1992; Arvidson and Östman, 1977). The thermogravimetric studies of cottonwood (*Populus spec.*) have shown that components of wood material (i.e. hemicelluloses, cellulose and lignin) start to degrade strongly at temperatures above 200 °C (Fengel and Wegener, 1984).

In wood moisture contents above FSP (i.e. in the free water region), the evaporation of water is assumed to occur with a relatively constant drying rate (Saastamoinen and Impola, 1994; Banerjee et al., 1998; Chen et al., 1999; Otwell et al. 2000; Spets, 2001). The capillary forces in wood structure are assumed to maintain both relatively uniform moisture distribution in wood particles, as well as the surface temperature equal to or slightly above the adiabatic saturation temperature of hot drying air. The cooling effect of water evaporation inhibits or retards the wood dry solids heating up to temperatures of above 100 °C and also the formation of organic emissions (Banerjee et al., 1995; Banerjee et al., 1998; Otwell et al., 2000; Spets, 2001). The profiles of selected VOC emissions from pine flakes during drying at 130, 160 and 200 °C, respectively, with air in a tube furnace are shown in Figure 3 as a function of wood moisture content (Otwell et al., 2000). The VOC emissions increase sharply at moisture contents of 5-10 % with drying air temperatures of 130-200 °C (Otwell et al., 2000). The corresponding VOC emission profiles from drying aspen flakes were found to act in the same way as from drying pine flakes (Otwell et al., 2000).

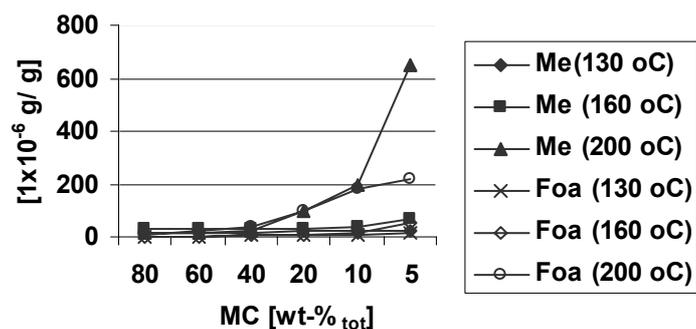


Figure 3. Selected VOC emission profiles [$\mu\text{g} / \text{g}$ dry solids] from pine lakes drying at 130, 160 and 200 °C as function of wood moisture content (MC,%). Me corresponds to methanol (i.e. CH_3OH), and Foa corresponds to formaldehyde (i.e. HCHO). Approximate curves are drawn according to data by Otwell et al., 2000.

However, the moisture profiles of wood particles do not remain uniform, and drying does not happen at a constant rate over a long time, even above wood FSP. The increase in the temperature of wood particle surfaces and dry solids above FSP have been detected in laboratory scale drying tests using wood (Nordic pine) chips in a batch fixed bed dryer, and in drying tests with birch (*Betula*) and pine (*Pinus Silvestris*) in a thermo-balance reactor (Saastamoinen and Impola, 1994; Holmberg and Ahtila, 2002). In both kinds of tests, the drying air temperatures were below 200 °C.

The lipids in wood may have some effect on wood drying mechanisms. The surface wettability of yellow birchwood (*Betula Lutea*) was examined by heating wood strips in air of temperatures of between 105 and 220 °C (Hemingway, 1969). There was a marked reduction of wood-surface wettability after heating in air; it was suggested, therefore, that under heat conditions the unsaturated fatty acids and esters undergo oxidation reactions that produce water repellency and a reduction of surface wettability (Hemingway, 1969). Concerning the saturated fatty acids, fresh wood contains only around 40 ppm (dry weight) of saturated free fatty acids, which was proposed to be too low a content to cause changes in surface wettability (Hemingway, 1969).

Finally, wood-particle dimensions have an influence on drying time, during which particles attain their final moisture content (Spets and Ahtila, 2001, USA). In the focused wood drying operation in the CHP plant, calculations for spherical wood particles showed five times longer drying times for wood spheres of 15 mm diameter than for wood spheres of 5 mm diameter (Spets and Ahtila, 2001, USA). A initial moisture content was 57.5 wt-% $_{\text{H}_2\text{O}_{\text{tot}}}$. Thus, the small particles in a heterogeneous bulk flow of wood are over-dried within the same time as larger particles attain their

set-up final moisture content. Heating of these small particles up to temperatures of over 100 °C leads to the formation of emissions from the wood drying operation.

DISCUSSION OF WOOD DRYING EMISSIONS

In the MSDS, the highest drying air temperatures are proposed to be in values around 185 to 200 °C, so the organic emissions from wood drying are expected to consist mainly of wood extractives. From the amounts of extractives in wood shown in Table 1, it can be estimated that especially bark drying may release high quantities of organic emissions, and thus affect the operability of the MSDS.

Direct evaporation and steam distillation become more obvious as both the partial pressure of water vapour of drying air and the drying air temperatures increase in consecutive drying stages in the MSDS as shown in Figures 1-2, due to increases in both the adiabatic saturation temperatures of hot drying, and in the corresponding water vapour partial pressures of the saturated air in the last drying stages of the MSDS.

Wood thermal degradation becomes obvious as the moisture profile of wood particles is not uniform in drying or when small particle are over-dried, which causes a temperature increase in the dry wood solid. In temperatures of up to 200 °C wood thermal degradation occurs mainly on the outer surface of the wood particles.

VOCs are reported to be emitted after most of the water is removed, due to the cooling effect of water evaporation. The non-condensable VOCs in exhaust drying air from the MSDS are fed into to the combustion unit in gaseous form, along with the combustion airflow. The condensable VOCs condense from the exhaust drying air if the air is cooled sufficiently. These condensations are basically prevented in a closed MSDS structure, because drying air is not cooled down to outdoor air temperatures between drying stages. When exhaust drying air cooling units are used, the condensed water from the MSDS has a high organic load and may be acidic. It is proposed, that drying air feed temperatures of the MSDS can be adjusted according to particular wood species or species groups in order to control and minimize organic load of the condensed water.

Emissions of VOCs, and thus risk of deposit formation on surfaces of the equipment in the MSDS, become obvious when the inlet drying air becomes warmer. Similarly, when the end moisture of wood in the drying stage is lower, the dimensions of the wood particles are smaller, and the difference between the temperature of the exhaust drying air and the adiabatic saturation temperature of the hot inlet drying air is smaller. The carry over of solid particles can be avoided or minimized by using small drying air velocities in the drying stages (i.e. in fixed-bed operations), as well as by installing mechanical particle separators in the drying stages.

EXPERIMENTAL

The organic emissions (both gaseous and in condensed water) from wood drying with inlet drying air temperatures near 100 °C were studied to confirm that the exhaust drying air could be out-purged into the atmosphere at the low temperatures applied in the MSDS. Both the organic (i.e. COD) and inorganic (i.e. total phosphate) contents in the condensed water from exhaust drying air cooling were equally investigated. Some of the results were presented in Ref. (Koivisto, 2000).

Apparatus

In Figure 4, the flow sheet of the test system is shown. The moist wood was fed into the top of a fixed bed dryer with a scraper conveyor. The dried wood was taken from the bottom of the dryer and fed into the combustor of the operating heating center by means of a screw feeder. The mixture of atmospheric drying and combustion airs (i.e. total air) in the tests was heated up indirectly up to three different temperatures of 80, 100 and 120 °C using the exhaust air of the dryer together with the flue gases from the combustor. Cooled exhaust drying air was out-purged into the atmosphere.

Instrumental Analysis

The exhaust drying air of the dryer was analysed with Fourier Transfer Infrared (FTIR Gasmeter) spectroscopy. The FTIR spectroscopy was used because of its capability of continuous monitoring organic emissions and air humidity under field conditions, and because of the favourable experiences in measuring odorous and process gasses in pulp mills and other process industries using FTIR spectroscopy. The FTIR calibrations were completed using pure components. Air volume flow and solid content were determined according to the standards SFS 3866 and SFS 5623. The measurements were performed in the air duct downstream after the dryer (exhaust air analysis and particle measurement, marked as 'W' in Figure 4), and the total air pre-heater (continuous exhaust air flow measurement with Pitot, marked as 'FI' in Figure 4). Temperature values were collected and saved in the data logger (marked as 'TI' in Figure 4). Humidity and temperature values of outdoor air were measured with a TSI-meter (single measurements during tests).

The exhaust drying air was filtered for particles and the sample air was heated up to a temperature of 150 °C and fed into the FTIR analyser. After the FTIR, the sample air was cooled and fed as dry airflow into an O₂-analyser. Uncertainties (with 95 % confidence) for the analysis (given by the measurer) are:

- for all monoterpenes +/-3 ppm (in the range from 0.5 to 100 ppm),

- for formic acid +/- 4 ppm (in the range from 1 to 100 ppm) and
- for particles +/- 35 % (with 95% confidence, relatively). Particle measurement includes uncertainty due to formation of particle deposits in the air duct. Particle emissions were calculated as the average value of four samples during each test.

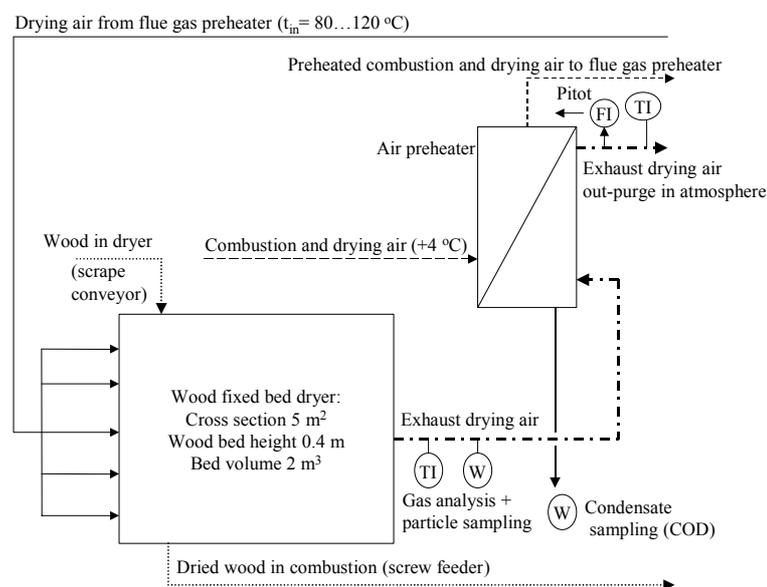


Figure 4. Flow sheet of test system.

Wood moisture content before and after the dryer were determined from single samples by heating them for about 24 h in an incubator at a temperature of 105 °C (± 5 °C). Condensate samples were taken from the total air pre-heater. pH measurements of condensate samples were carried out with a Metrohm 632 pH meter. The chemical oxygen demand (COD) of condensate samples was determined by oxidizing the samples with permanganate according to standard of SFS 3036. The conductivities of condensate samples were measured with an E518 Metrohm Herisau meter, and the total phosphorus content according to the standard SFS3026.

Test conditions and wood material

The wintertime outdoor air temperature in the tests was 4 °C. The relative outdoor air humidity (RH) varied between 79 and 86.5 % . The wood in the first test consisted of a mixture of Nordic wood species of birch, spruce and pine. In the second test, logging residues was employed (mixture of Nordic softwoods spruce and pine), of which spruce was dominant. The average total mass flow of mixed chips was 163 kg/h (5.8 hours), and of logging residues 341 kg/h (3.8 hours). The wood properties in the tests are given in Tables 3 (moisture contents) and 4 (wood particle size distributions).

Table 3. Wood moistures in drying tests.

Wood matter	Inlet drying air temperature [°C]	Average wood moisture before dryer [wt% _{tot}]	Average wood moisture after dryer [wt% _{tot}]
Mixed chips	80	41	32
Mixed chips	100	41.5	36.5
Mixed chips	120	42.5	14.5
Logging residues	80	68	41
Logging residues	100	68	59.5

Table 4. Wood particle size distributions in dryer feed (approxim. sieve analysis).

Size (mm)	< 5	5-16	16-24	> 24	Σ line [wt-%]
Mixed chips	12	35	38	15	100
Logging residues	39	23	22	16	100

The exhaust drying air properties

The drying air flows, temperatures and humidities of feed in the dryer are shown in Table 5. Adiabatic saturation temperatures of hot drying air in tests are calculated with the applied Clausius-Clapeyron equation (Spets, 2001; Spets and Ahtila, 2001, USA and Norway).

Table 5. Drying air values in tests.

Wood matter	Inlet air temp. [°C]	Inlet air humidity [vol-%]	Ad. satur. temp. of inlet air [°C]	Average drying air flow [m ³ n/ s (dry)]	Cooled exhaust air temperature [°C]
Mixed chips	80	0.64	28	1.10	31
Mixed chips	100	0.65	32	0.76	37
Mixed chips	120	0.65	35	0.52	36
Logging residues	80	0.66	28	1.01	32
Logging residues	100	0.70	32	0.46	36

DISCUSSION OF EXPERIMENTAL RESULTS

The results for detected organic gaseous components in the exhaust drying air are shown in Table 6. As a result of mild outdoor air temperature during test days, the heat consumption in the local area was both small and unsteady, while the combustor of the heating centre operated constantly with loads below its nominal fuel effect of

500 kW. The drying air flows at higher inlet temperature tests of 100 and 120 °C were reduced from the test values with an inlet temperature of 80 °C, because of limited heating capacity of the flue gas flow from the combustor (see Table 5).

In Table 7, the organic emissions in units of [g / kg input wood dry solids] are shown with the mass flow of dry solids calculated from the average total mass flow in each test. Concentration values below the lower detection limit of FTIR (in Table 6), were set to 0.

The detected organic gaseous emissions in the exhaust air of the dryer were monoterpenes and formic acid (Table 6), which except for terpinolene emission in the logging-residue tests, were near the lower detection limits of the FTIR. Although the drying airflows were not equal in all tests, the results in Tables 6 and 7 indicate large difference in organic emissions from mixed chip and of logging residue drying. Although the amount of condensed organic material on solid particles in the exhaust drying air of the dryer (Tables 6 and 7) cannot be estimated, the VOC-emissions from the low temperature drying air stage of the MSDS are proposed to be of the same order of magnitude as is naturally emitted from the forest by total terpene emissions in Ref (Juuti, 1991).

Table 6. Detected average organic compounds' (gaseous and particles) concentrations in airflows from the fixed bed dryer in different tests. All values are given for dry flows and NTP (0 °C, 1.013 bar). 0* corresponds to values under FTIR lower detection limits.

Wood matter	Drying air inlet temp. [°C]	α - pinene [ppm]	β - pinene [ppm]	3 - careene [ppm]	R- limonene [ppm]	Terpinolene [ppm]	Formic acid [ppm]
Mixed chips	80	0*	0.5	0*	0*	1	0.5
Mixed chips	100	0*	0.8	0*	0*	1	0*
Mixed chips	120	0.7	1.2	0.9	0*	1	0*
Logging residues	80	0*	3.2	2.5	0*	6	1.3
Logging residues	100	0*	4.9	5.2	0*	11	2.2
Particle emission in mixed chip tests:		Max. 0.6 mg/m ³ ,dry (with drying air inlet temp. of 80 °C)					
Particle emission in logging residues tests:		Max. 6.0 mg/m ³ ,dry (with drying air inlet temp. of 80 °C)					

Table 7. Detected organic gaseous emissions from / input to wood dry solids.

Wood matter	Drying air inlet temp. [°C]	Organic emission [g / kg input wood dry solids]
Mixed chips	80	0.4
Mixed chips	100	0.3
Mixed chips	120	0.5
Logging residues	80	2.6
Logging residues	100	2.1

The pH-values of chemical oxygen demand (COD), conductivity, total phosphate and particle concentrations of condensed water samples in different tests are shown in Table 8.

Table 8. Analytical results of condensate samples in tests.

Wood matter	Drying air inlet temp. [°C]	pH value	COD _{Mn} [mg/dm ³]	Conductivity [μ S/cm]	Total phosphate concentration [μ g/dm ³]	Particle concentration [mg/dm ³]
Mixed chips	80	5.9	42	33	340	27
Mixed chips	100	6.0	56	39	340	23
Mixed chips	120	6.2	80	41	344	29
Logging residues	80	5.9	55	87	1540	56
Logging residues	100	5.9	110	92	808	14

It can be speculated from the results in Tables 6-7 that the out-purge into the atmosphere of all exhaust drying air from the secondary energy heated drying stage in the MSDS is allowed. The feed air temperature in the secondary energy heated drying stage has to be adjusted according to certain maximum values, which depend on each wood species, and on the final moisture content of wood in drying stage. For example, VOC emissions from pine drying (*Pinus ponderosa*) have been reported to increase by 34 % as the drying temperature increased within the range of 68-85 °C, when the lumber was dried from green moisture content to 12 % moisture content (Milota and Lavery, 2003). As exhaust drying air contains particles (Table 6), it may be advised to equip all the drying stages in the MSDS with mechanical particle separator in order to remove these particles from the exhaust air.

It is also suggested that the results in Tables 6 and 7 for mixed chips are comparable and compatible with the results reported earlier for the amounts of organic emissions released from pine bark drying with short delay times in the laboratory-scale steam

dryer (Fagernäs, 1992; Fagernäs, 1993). As far as drying air temperature is concerned, the order of magnitude of the detected organic emissions from the wood-based biomass dry solid content shown in Table 7 fit in with the values shown in Table 2. Detected emissions for logging residues in Tables 6 and 7 fit also in with those reported in literature reviews. Differences in values of detected organic emissions in Tables 6 and 7 between mixed chips and logging residues can be explained by the differences in extractable concentrations in different parts of different wood species, as shown in Table 1.

The analytical results of samples from condensed water vapour (Table 8) show that COD values were low when compared to reported COD values of condensed water from different wood-based biomass steam dryers (Fagernäs and Sipilä, 1996). Detected pH values of condensed water were also comparable to shown values in Ref (Fagernäs and Sipilä, 1996). Samples of condensed water vapour from wood drying were shown to have inorganic loads (i.e. total phosphate, as shown in Table 8), which has to be taken in account when considering the treatment method for these condensed water flows from the MSDS in the waste water plant of integrated pulp and paper mills.

CONCLUDING REMARKS

The new multistage drying system (MSDS) for wood-based biomass drying offers promising solution possibilities in CHPs, especially in integrated pulp and paper mills where there exist both high quantities of wood residues from pulp and paper making processes and heating sources of different temperature levels.

The amount of VOC emissions from low inlet drying air temperature (near 80 °C) biomass dryer was detected to be low, and the emissions are proposed to be of the same order as emitted from forests by natural monoterpene emissions.

According to literature reviews, it is proposed that VOC emissions from wood-based biomass drying with higher temperature drying air (between 100 and 200 °C) are substantially smaller, when wood final moisture content corresponds to the FSP. Emissions from wood-flake drying at temperatures between 130 and 160 °C have been reported earlier to increase substantially only if wood is dried to a final moisture content of 5-10 wt%_{H₂O,tot.}. The effects on the environment of non-condensable emissions of VOCs should not be serious, because these VOCs are led in gaseous form into the combustion unit as a part of total combustion air. Condensable VOCs were reported earlier to be emitted from wood at temperatures near 200 °C, so somewhere within the temperature range of 130-200 °C there may be a 'safe' value for the upper temperature limit for minimizing condensable VOC emissions from wood drying. Mechanical particle separators, installed between each drying stage,

may help to remove condensable VOCs from the exhaust drying air flow with solid particles, because these VOCs tend to enrich on small particle surfaces.

If the MSDS includes heat recovery units, which are accomplished by exhaust drying air cooling, the acidic water contains both inorganic and organic compounds. The amount of organic compounds in condensed water from the MSDS could perhaps be minimized by adjusting drying air feed temperatures according to the wood species to approximately 80 °C in the low temperature drying air stage, and between temperatures of 130 and 200 °C in the high temperature drying air stages.

The suggested operability of the MSDS for wood drying is proposed for drying air temperatures of up to 130-200 °C, when the lowest wood final moisture content is FSP. Reducing or eliminating both exhaust drying airflows direct to the atmosphere and the formation of condensed water, MSDS is regarded as an environmentally fairly safe drying process, especially in comparison to earlier dryer technologies. The installation in MSDSs of different types of biofuel combustors could produce both energy efficient and environmentally safe applications of integrations within a wide range of fuel effect.

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