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Enhancement of the Use of Wood Fuels in Heat and Power Production in Integrated Pulp and Paper Mills

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Dissertation for the degree of Doctor of Technology to be presented with due permission for public examination and debate in Auditorium K 215 at Helsinki University of Technology (Espoo, Finland) on the 12th of December, 2003, at 12 o'clock noon.

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ABSTRACT

The drying of moist biofuels such as wood-based biomasses should be as effluent-free and as energy-efficient as possible in order to ensure the safe and economical operation of industrial CHP plants. This work presents a multistage drying system (MSDS), which provides significant benefits in comparison with earlier conventional single dryer systems. This new application is installed most promisingly in integrated pulp and paper mills. The MSDS, which simultaneously uses secondary process energy, as well as backpressure and extraction steam as the drying energy, enables a smaller volume flow of drying air than single dryer systems. Depending on the structure of the system, up to 100 % of the exhaust drying air can be utilized as combustion air. The use of MSDSs enables an increase in CHP plant boiler capacity, which in turn boosts the production of power and heat in combined heat and power (CHP) plants. Additionally, the improvement in CHP can be achieved with reduced organic emissions from moist biomass drying. Also, the amount of unburned organic compounds and of CO in flue gases from combustion is reduced as a result of the improved quality of the biofuels. When compared to direct steam drying, the MSDS also better minimizes, or even eliminates, the formation of organically loaded condensates in the drying operation.

PREFACE

The work reported in this thesis has been carried out at the Laboratory of Energy Economics and Power plant Engineering, Helsinki University of Technology, during the period 1999-2003.

Otaniemi, August 2003

Jukka-Pekka Spets

TABLE OF CONTENTS

LIST OF SYMBOLS AND NOTATIONS

SYMBOLS

c_p	heat capacity [kJ/kg K]
CHP	combined heat and power production
CHP efficiency	ratio of power or heat or sum of power and heat values to fuel input of CHP plant boiler [%]
d	drying
da	dry air
DS or ds	dry solids of wood or biomass in combustion in CHP plant boiler
ESP	electrostatic precipitator
(B)FBB	(bubbling) fluidised bed boiler
FFE	fuel feed and transport system of CHP plant boiler and of integrated drying and boiler-plant systems
FSP	fibre saturation point of wood-based biomass
FWT	feed water tank in steam system
h	hot or heating
H	symbol for steam-heated drying stage in MSDS or heat flow for use of integrated paper and pulp mills [MW_{th}]
HE	indirect air-air heat exchanger
i	enthalpy [kJ/kg da]
q_{iw}	effective heating value of fuel [kJ/kg moist fuel]
luvo	combustion air preheater (i.e. luft vorwärmer)
$\dot{m}$	mass flow [kg/s]
$\dot{m}''$	water evaporation flux through wood particle's outer surface [kg/m^2s]
MSDS	multistage drying system
n	number of drying stages in drying system
p	pressure or vapour pressure
P	electric power [MW_e]
R	universal gas constant (= $8.314 \dfrac{J}{molK}$)
S	symbol for drying stage heated by secondary process energy in MSDS
SEC	specific energy (i.e. heat) consumption of drying [kJ/kg evaporated water]
SEC_{rd}	reduced specific energy consumption of drying as extraction and backpressure steam from steam turbine
Scr.	exhaust drying air-cooling and water condensing unit (i.e. scrubber)
t	temperature [^oC]
T	temperature [K]
u	velocity of drying air through a drying stage cross-section area [m/s]
w	water
x	air moisture ratio [kg H_2O/kg da] or variable

X	moisture content [wt-%tot] or moisture ratio [kg_{H2O}/kg ds] of wood or peat
z	number of gaseous components in drying air

INDICES

b-p	backpressure (steam from steam turbine)
Boil	boiler
d, D	drying
e	electric
extr	extracted (steam from steam turbine)
evp	evaporation
ex	extra
f	fuel
fin	final
g	gas (i.e. atmospheric or exhaust drying air)
gen	electric generator in steam system
H	heating
hp	high-pressure part of steam turbine
evp	evaporation
i	drying stage of number i from n drying stages in MSDS or gaseous component of drying air
ihc	internal heat consumption [MW_{th}]
in	inlet or input (also notation of 1)
ipc	internal power consumption [MW_e or $kWe/MW_{th, steam\ effect\ of\ CHP\ plant\ boiler}$]
lp	low-pressure part of steam turbine
LS	live steam (or high pressure steam from CHP plant boiler)
net	for net output CHP values after reductions of internal power and heat consumptions of process equipment in integrated drying and boiler-plant systems
o	reference [e.g. T_o reference temperature for heat balance (= 0.01 ^{o}C)] or initial
out	outlet or output (also notation of 2)
outdoor	outdoor air (i.e. atmospheric air)
rd	reduced
s	saturation (state) (i.e. 100 % saturated with water vapour), outer surface or slip velocity [i.e. velocity difference between particle and air , m/s]
th	thermal
tot	total
w	water

NOTATIONS FOR MSDS STRUCTURES

nH	MSDS structure consisting of n (n=1-4) steam-heated drying stages
S+(n-1)H	MSDS structure consisting of 1 drying stage heated by secondary process energy and (n-1) (i.e. total n=2-5) steam-heated drying stages

$(t_{gout}-t_s)_i = t$	difference between exhaust drying air temperature and adiabatic saturation temperature of hot drying air at the inlet to drying stage i [^oC, equal for all drying stages in MSDS]
$(t_{gout}-t_s)_i = t_1+t_2$	-"- [^oC, t_1 for secondary energy heated drying stage + t_2 for steam-heated drying stages]
xx-yy…zz	wood drying sequence in MSDS: Moisture content of wood in secondary energy heated drying stage- in first steam-heated drying stage … out last steam-heated drying stage [wt-%$_{H2Otot}$]

GREEK

α	convective heat transfer coefficient [W/m^2 K]
Δ	delta (i.e. change or difference)
λ	heat of water vaporization [KJ/kg] or excess-air factor in combustion
η	efficiency [%]
τ	time delay [s]
Φ	heat flow [kW$_{th}$] or electric power [kW$_e$]
$\sum_{i=1}^{n}$	sum of 1st to nth variables

LIST OF ORIGINAL PAPERS AND PATENTS

This thesis is based on the following papers, which are referred to as I to V in the text. Additional unpublished data are also presented.

(I.)   Spets, J.-P. 2001: A New Multistage Drying System. In: Proceedings of 1st Nordic Drying Conference 27th-29th June in Trondheim, Norway, Paper No. 13. ISBN 82-94-2073-2.
Reprinted with permission: (c) Copyright 2001. 1st Nordic Drying Conference. SINTEF Energy Research. Trondheim, Norway.

(II.)   Spets, J.-P. & Ahtila, P. 2001: Preliminary Economical Examinations for a New Multistage Biofuel Drying System Integrated in Industrial CHP-power Plant. In: Proceedings of 1st Nordic Drying Conference 27th-29th June in Trondheim, Norway, Paper No. 14. ISBN 82-94-2073-2.
Reprinted with permission: (c) Copyright 2001. 1st Nordic Drying Conference. SINTEF Energy Research. Trondheim, Norway.

(III.)   Spets, J.-P. & Ahtila, P. 2001: A New Multistage Biofuel Drying System Integrated into an Industrial CHP-power Plant: Description of Process and Performance Calculations. In: Proceedings of 2001 ACEEE Summer Study on Energy Efficiency in Industry Vol. 2, July 24th-27th New York, USA, Pp. 67-78.
Reprinted with permission: (c) Copyright 2001. Proceedings from the 2001 ACEEE Summer Study on Energy Efficiency in Industry. USA.

(IV.)   Spets, J.-P. & Ahtila P. Improving the power-to-heat ratio in CHP plants by means of a biofuel multistage drying system. Appl. Therm. Eng. 22(2002)10, Pp. 1175-1180.
Reprinted with permission: (c) Copyright 2002. Applied Thermal Engineering. Elsevier Science Ltd.

(V.)   Spets, J.-P. & Ahtila P. Reduction of organic emissions by using a multistage drying system for wood-based biomasses. Accepted for publication in Drying Technology - An International Journal. Marcel Dekker, Inc.
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The disputant bears full responsibility for devising the actual work and writing the manuscripts. Professors M. J. Lampinen and P. Ahtila have had considerable involvement in the theoretical development of the included articles I-V. Professor T. M. Raunemaa has had considerable involvement in the theoretical development of the included article V. All professors have reviewed the manuscripts precisely and critically. Prof. P. Ahtila was the supervisor of the work; Prof. M. J. Lampinen was my first instructor (energy subjects) and Prof. T. M. Raunemaa my second instructor (emission subjects).

PATENTS

FI 106817 B. 12th April, 2002. Patent. Järjestelmä kostean biomassaperäisen polttoaineen kuivaamiseksi. (System for the drying of damp biomass-based fuel). Ahtila, P. & Spets, J-P.

US 6588349. 8th June, 2003. Patent. System for the drying of damp biomass-based fuel. Ahtila, P. & Spets, J-P.

1 INTRODUCTION

1.1 Role of bioenergy in the Finnish forest industry

The largest producer and consumer of bioenergy in Finland nowadays and for the foreseeable future is the Finnish forest industry, in which waste liquors, wood bark and other wood-based biomass by-products from processes account for over 60 % of the total biomass consumption in Finland, e.g. 5.6 Mtoe in 1992 (Helynen & Nousiainen 1996). The Finnish forest industry will have increased its basic operations using biomass fuel by 2.1 Mtoe by the end of the period 1992- 2010 (Helynen & Nousiainen 1996). Of that increase, biomass by-products from processes will make up 85 %. Figures 1 and 2 show the distribution of the use of fuel and power consumption in the Finnish forest industry for the period 1985-2001.
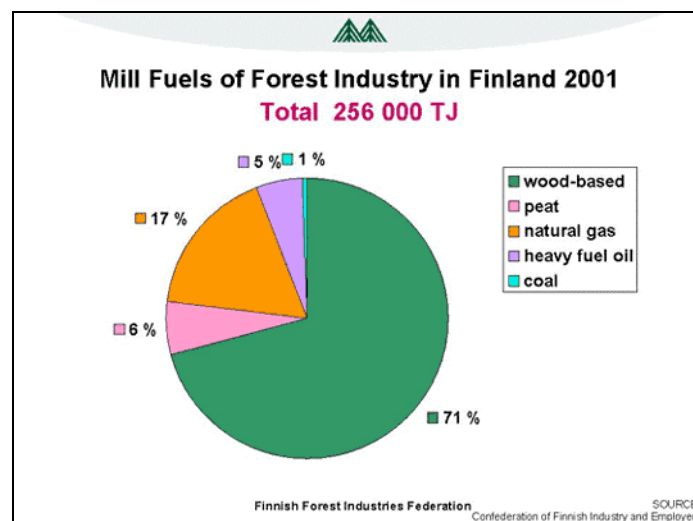
Figure 1. Mill Fuels of the Forest Industry in Finland (http:/english.forestindustries.fi).
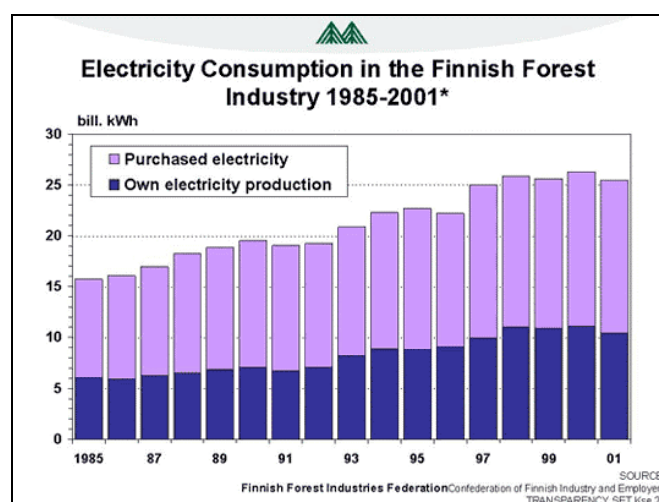
Figure 2. Electricity Consumption in the Finnish Forest Industry 1985-2001 (http:/enlish.forestindustries.fi).

In Figure 1, wood-based fuels cover the sum of black liquor from pulp-making processes and of other wood-based biomasses (e.g. chips, forest residues). From Figure 2, it can be seen that the electricity consumption of the forest industry has grown as a function of increased production capacity, and the ratio of purchased electricity to own electricity production has remained constant over time.

The use of bioenergy both in separate power and heat production and in combined heat and power production (CHP) has grown noticeably in Finland during recent years. In 2000, the proportion of bioenergy in total primary energy consumption in Finland was of an order of magnitude of 25 % (i.e. 90 TW_h, which also includes peat consumption), which corresponds to nearly 8 Mtoe (Kuitto 2002). The total primary energy consumption in Finland in 2000 was of an order of magnitude of 32 Mtoe (http://tilastokeskus.fi/tk/…).

Combustion technology in the Finnish forest industry

The combustion of wood-based biomass usually occurs in grate-fired or fluidised bed boilers within a steam effect range of 5-50 MW_{th} (Lahtinen & Komppula 1996). Earlier, the grate-fired boilers were favoured over fluidised bed boilers in the 5…20 MW_{th} area because of their easier operability (Wimmerstedt 1999). The operability of fluidised bed boilers is based on a control system, while the combustion process of grate-fired boilers in furnaces can be easily monitored in a control-room through the use of camera equipment. Progressively improved and lower-priced pc-based control systems of combustion processes have enabled fluidised bed boiler applications down to 5 MW_{th} (Kinni, 1998-2000). The fluidised bed boilers can be kept as an alternative to grate-fired boilers, especially in applications down to thermal output of 10…15 MW_{th} (Kinni 1998-2000). In large-scale applications, fluidised bed boilers are now dominant on the market, with both bubbling fluidised bed (BFBB) and circulating fluidised bed boilers (CFBB) being used for biofuel firing (Wimmerstedt 1999).

Grate-fired boilers are sensitive to fuel moisture content. If grate-fired boilers are designed for moist fuel, the first part of the grate is designed as a band dryer. If grate-fired boilers are fired with fuels of low moisture content, cooling of the grate by the combustion air must be foreseen (Wimmerstedt 1999). Large-scale applications of suspension-fired boilers with reversed flue gas conduction have been especially developed for the combustion of dry biofuels (Wimmerstedt 1999). With fluidised bed boilers, fuel with a low moisture content results in an excessively high combustion temperature and the agglomeration of sand material in the bed. When fuel has a low moisture content, the fluidised bed operation needs flue gas recycling in the bed to lower the oxygen concentration in the combustion air (Kinni 1998-2000).

1.2 Moist biomass drying before combustion

The starting-point for this research work was the fact that moist fuel pre-drying before combustion enables both improved heat formation and decreased formation of unburned organic gaseous emissions from the combustion process, as was found in the pilot literature survey (Spets 1998). Moist fuel drying before combustion enables the following propitious influences on combustion (Tillman 1981, Anttonen 1996): 1. Increase in adiabatic combustion temperature. 2. Decrease in combustion excess-air

factor. 3. Decrease in the mass flow of carry-over particles in flue gases. 4. Decrease in emissions of gaseous unburned organic compounds from combustion. CO_x, NO_x and heavy metals are reduced mainly as a result of a decrease in the fuel mass flow in combustion after moist fuel drying.

Pulp and paper making processes release many wood rejects (residues, chips, bark, branch, knots). These moist wood-based biofuels could be dried before combustion partly with low-temperature secondary process energy flows (e.g. flue gases, hot process condensates) as drying energy sources. The utilization of secondary process energy flows in drying mentioned earlier improves the energy efficiency of integrated pulp and paper mills, allowing replacement of purchased fuels. The improved energy efficiency of integrated pulp and paper mills decreases the primary energy consumption per produced mass of pulp and paper (Ahtila and Svinhufvud 1998, Martin et al 2000).

1.3 Earlier problems in moist biomass drying operations

Moist biofuels (e.g. wood-based biomass and peat) have been dried in different kinds of single-stage applications of flue gas, air and steam dryers, which have produced increases in boiler efficiencies, both in power and in heat production – separately or together (Anttonen 1996, Siitonen 1996).

The flue gas drying of biofuels produces organic emissions, which have set limitations on their drying and capacity. In steam drying systems, the organic compounds loaded condensates, which have high COD values, are problematic. Therefore, the waste water treatment systems associated with biofuel steam drying plants require a great deal of investment and have high operational costs (Wimmerstedt 1999). With flue gas dryers, the corresponding gaseous emissions from moist biofuel flue gas drying are 2-6 times higher than corresponding organic loads in condensates from wet biofuel steam drying (Munter & Bäcker 1993).

Regulations aimed at preventing air pollution have required treatment of the exhaust drying gas or air from the drying stage before discharge into the atmosphere. It is possible to treat these exhaust drying gases or air thermally at temperatures of approximately 760 $^{\circ}$C, when different gaseous organic compounds react completely with oxygen to form carbon dioxide and water (WBPI 1993). It is possible for such thermal treatment to occur in a combustion device, in which the exhaust drying gas is led in combustion along total combustion air. This has raised the need to accomplish integrated dryer or drying system and boiler-plant systems that eliminates discharges of organically loaded exhaust gases and condensates into the environment.

Different kinds of integrated drying and boiler-plant systems were developed between the 1970s and 1990s, and this development work is still on-going. Different combustor and dryer technologies have been integrated with respect to drying different kind of moist fuels (e.g. coal and biofuels). In all kinds of air or flue gas dryers containing integrations of various kinds and applications, it has been difficult to simultaneously combine high moisture reduction of fuel and all exhaust drying gas or air treatment in corresponding combustion devices without adversely affecting the performance of the boiler (NCASI 1983). This is why a proportion of exhaust drying gas has to be drawn into other treatment systems (i.e. condensing flue gas scrubbers, filters, catalytic systems etc.) before discharge into the atmosphere or other combustion devices. As a result of the problems involved in treating exhaust drying gases, moist fuel pre-drying has to be performed with minor reduction of the initial moisture content.

A direct contact drying system means that the heating medium (gas or steam) is in direct contact with the moist fuel. Indirect contact drying means that heat is transferred from the heating medium to the moist fuel through heat transfer surfaces (i.e. the heating agent and moist fuel are not in physical contact with each other).

According to patent searches made during the period 1970 - 1998, the following conclusion can drawn:

1. Dryer applications have concentrated on steam drying since the end of 1980s.

2. Indirect drying system - combustor integration is preferred to direct.

The preference for integrated indirect contact dryer and combustion systems is understandable, because the exhaust drying gas flow from the indirect- contact drying unit is much smaller than that from a direct- contact drying unit. The preference for steam drying over flue gas or air drying is understandable, because exhaust drying air or flue gas from the drying unit has a greater volume flow than water vapour from an indirect steam dryer. Also, heat recovery from an exhaust low-pressure steam flow occurs at a higher temperature level than heat recovery from, for example, exhaust drying air (Wimmerstedt 1999, Paper IV).

The moist fuel flue gas or air drying systems found in the patent searches mentioned earlier had one important thing in common: the moist fuel drying was applied in separate, single drying stages, which had separate fresh drying air or hot flue gas feeds. In a single stage drying system, the total moist fuel mass flows could be only partially dried before combustion, in the case that all the exhaust gas were to be led to the boiler (i.e. drying air or flue gas has a poor water-absorbing capacity).

2 THE SCOPE AND OBJECTIVES OF THE WORK

2.1 Background of the thesis

The main conclusion of the pre-studies before this thesis work was that research efforts in this field should concentrate on managing and decreasing organic emissions (i.e. as gases to atmosphere and in condensates) from biomass drying (Spets 1998). A certain type of multistage drying system (MSDS) and a particular application of it were selected for further evaluation (Papers I-V). The common features of the evaluated multistage drying processes were:

1. Use of heated air as the drying medium; 2. Indirect heating of the drying air by secondary process heat or process steam before each drying stage; 3. Direct contact of the drying air with the fuel (i.e. woody biomass) to be dried; 4. Use of the dried woody biomass as the main fuel with peat for a CHP plant boiler of integrated pulp and paper mill; 5. Use of the exhaust air from the dryer as combustion air in the same CHP plant boiler.

The process specifications of the specified CHP plant boiler were taken from an existing CHP plant in an integrated pulp and paper mill of Stora Enso in Northern Finland (i.e. the selected CHP plant, Papers II-V).

A patent has been granted for the innovative MSDS concept developed during the course of this work (FI 106817 B, US 6588349). The drying systems that were found in patent searches through the period of 1970 - 1998 did not have the same operation principle as this selected multistage drying system. The earlier known multistage drying systems were composed of two or more drying components that had their own drying air feeds as described in Walther (1988), for example. The exhaust drying gas or air was not heated between drying stages, and was not fed into the following drying stage. In the most likely multistage structures for drying systems, which were mentioned and shown in Ref ($\check{C}erma'k$ 1991), the directions of flows of drying air and of moist matter were different to those in the selected MSDS concept.

2.2 The objectives of the thesis

The main part of the thesis work comprised in-depth performance analyses of MSDSs. The rationale for using the exhaust air as combustion air is to completely elimimate emissions of organic compounds when drying wet biofuels to a great extent. As discussed in Chapter 1, earlier efforts to accomplish this with single-stage dryers were been unsuccessful because of the excessive amount of exhaust air from the dryer. The specific objectives of the performance analyses in this study were: 1. To determine the influence of the key process parameters on the performance of MSDS dryers, including comparisons with single stage dryers; 2. To obtain pre-design estimates of the potential enhancements in energy production arising from the application of MSDS process in conjunction with CHP plant boilers and 3. To confirm the feasibility of utilising the exhaust air from a MSDS among the total combustion air in a CHP plant boiler.

The pre-studies also identified two areas of potential technical uncertainty for MSDS: 1. Low biomass drying rates resulting from the application of relatively flow drying temperature of below 200 ^{o}C and 2. deposition of released organic compounds on surfaces of the drying equipment. Separate evaluations of these issues were conducted during the course of the thesis work. As part of the study of organic

emission, field measurements were made on an industrial dryer. On the basis of results of the investigations of emissions, the possibility of discharging the exhaust drying air from one or more stages directly into the atmosphere was assessed. This measure would further improve the performance of the CHP plant boiler integrated with the MSDS.

2.3 The scope of the thesis

The scope of this thesis work did not include the detailed design, sizing or costing of the MSDS equipment, nor the assessment of any impacts of the MSDS process on the design of the CHP plant boiler. It is envisaged that these activities will constitute the next phase of the process development work. The overview part of this thesis also contains some unpublished data, which were deemed to be particularly useful for future process development work.

3 MULTISTAGE DRYING SYSTEM

3.1 Different multistage drying systems evaluated

The principles of the closed (i.e. no drying air out-purges between drying stages) multistage drying system (MSDS) are shown in Figure 3 (Paper I). The exhaust drying air from the previous drying stage is led through an intermediate heater (indirect heating) to the following drying stage. Partially dried biofuel is led from the previous drying stage to the following one. The water absorption capacity of the drying air is greater than in a single stage drying system.
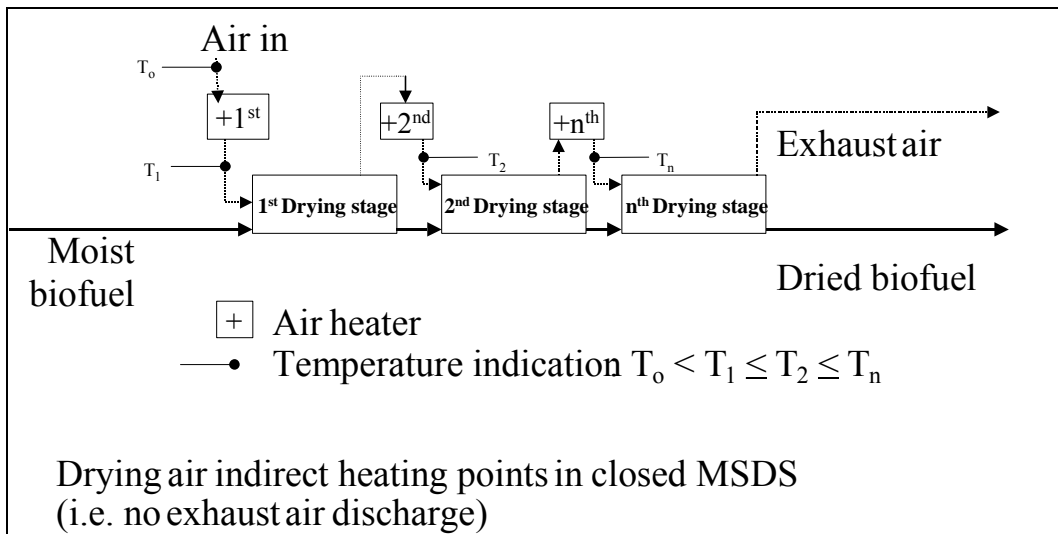
Figure 3. The closed multistage drying system (i.e. no exhaust drying air discharge between drying stages). Number of drying stages in the MSDS is n $\geq$ 2 (Paper I).

The principles of the open (i.e. partial discharge of drying air between drying stages) MSDS are shown in Figure 4. As a result of the partial discharge of exhaust drying air into the atmosphere, the humidity of the exhaust drying air from the final stage of MSDS is reduced. Indirect heat recovery from the out-purged drying air to feed drying air in the following drying stage is possible. This heat recovery reduces the primary heat consumption of the MSDS.

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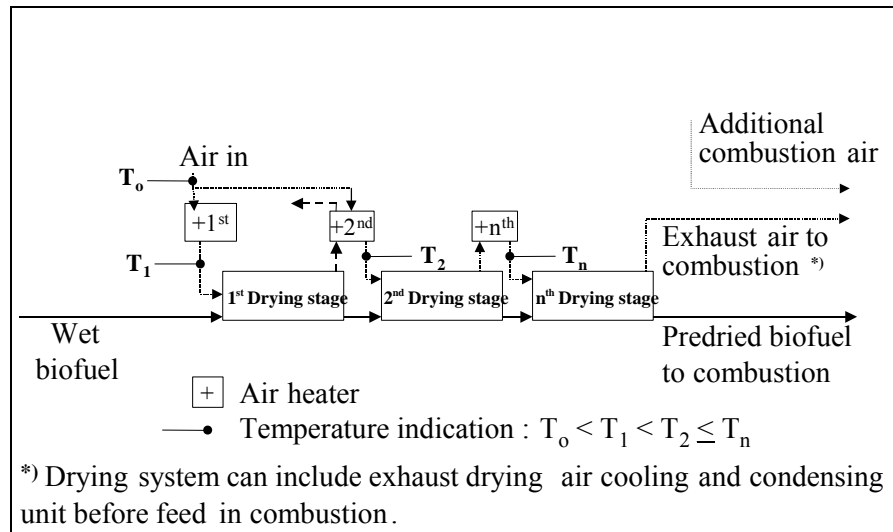
Figure 4. The open multistage drying system (MSDS) (Paper II-IV).

Figure 5 shows an application of MSDS for moist wood drying before combustion in a CHP plant boiler, e.g. in pulp mills.
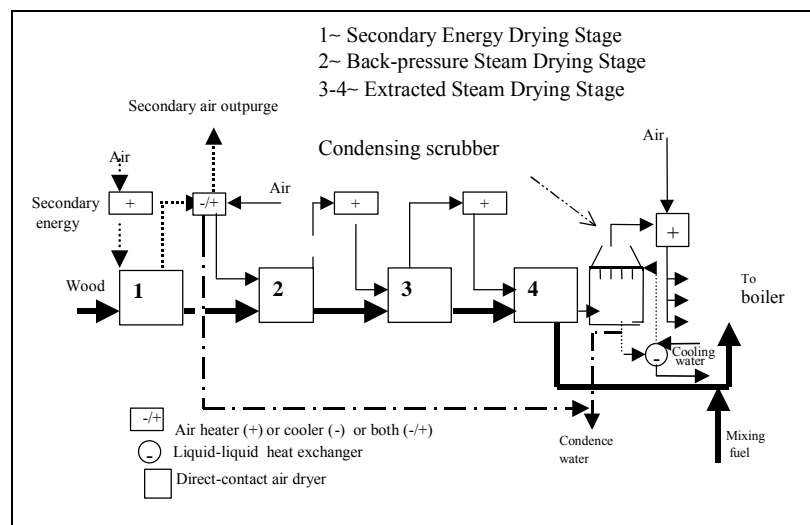
Figure 5. An application of MSDS for moist wood drying in conjunction with a CHP plant boiler (Papers II-IV).

In Figure 5 the heating of drying air for the first drying stage in the MSDS is accomplished with low-temperature secondary process energy (i.e. low-pressure steam or hot condensate). The heating of drying air for the second drying stage is accomplished with back-pressure steam from the steam turbine. The heating of drying air for the last drying stages is accomplished with extraction steam from the steam turbine. The exhaust drying air from the MSDS can be cooled in a cooling and condensing unit (e.g. a cooling scrubber) before being fed as combustion air to the CHP plant boiler. This cooling of the exhaust drying air reduces the water content of the

combustion air, and therefore the flue gas mass flow from the furnace. Indirect heat recovery from the circulated water of the scrubber can be accomplished as shown.

Table 1 shows the definitions of notations used herein to specify the drying operations in various MSDSs.

Table 1. Definitions of notations used to specify the drying operation in various MSDSs. (Papers I-V).

nH	Closed MSDS structure consisting of n (n=1-4) steam-heated drying stages
S+(n-1)H	Open MSDS structure consisting of 1 stage S heated by secondary process energy and (n-1) (i.e. total n=2-5) steam-heated drying stages H
$(t_{gout}-t_s)_i = t$	difference between exhaust drying air temperature and adiabatic saturation temperature t_s of hot drying air at the inlet to drying stage i [^{o}C, equal for all drying stages in MSDS]
$(t_{gout}-t_s)_i = t_1+t_2$ -"-	; t_1 for secondary energy heated drying stage + t_2 for steam-heated drying stages [^{o}C]
xx-yy…zz	wood drying sequence in MSDS: moisture content of wood in secondary energy heated drying stage - in first steam-heated drying stage … out last steam-heated drying stage [wt-%$_{H2Otot}$]

3.2 Theory and equations used for analysing drying systems

3.2.1 Theory for the multistage drying system

The operation principles of single stage drying and of the selected closed-structure multistage drying systems (MSDSs) are shown in the Mollier (i,x)-diagram as Salin-Soininen perspective transformations in Figures 6-7 (Paper I). Compared with the single stage drying systems, the MSDS can operate with lower inlet air feed temperatures in each of the single drying stages, if the air flow rate is kept the same (Fig. 6). On the other hand, if the temperatures are fixed as in one stage drying, then the airflow rate can be reduced as a result of increased water absorption capacity (Fig. 7).

The calculated results for wood drying in different drying systems with 1-4 drying stages are shown. Drying air feed temperatures in drying stages in different drying systems vary between 50 and 130 ^{o}C. The outdoor air temperature varies between –15 C and +15 ^{o}C. Critical examinations of calculated results are given. Simplifications are described in Papers I-IV. Different heat losses in the atmosphere are not taken into account.
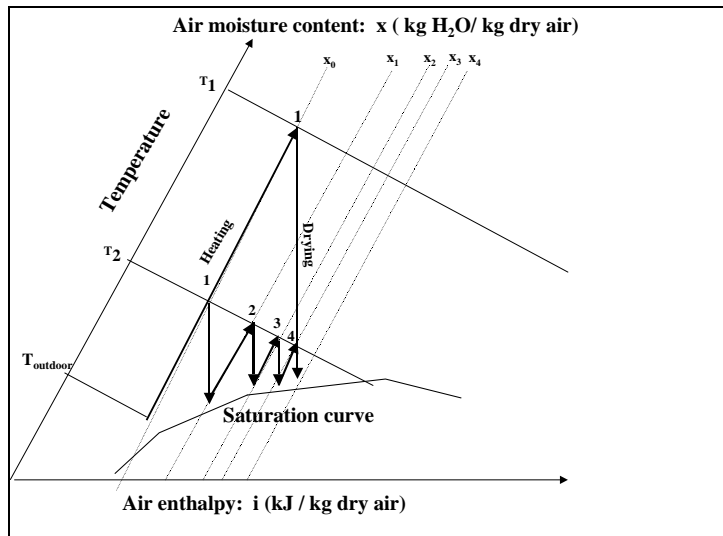
Figure 6. Comparison of one stage and multistage drying systems with lower inlet air temperatures in Mollier (i,x)-diagram as a Salin-Soininen perspective transformation (Paper I).
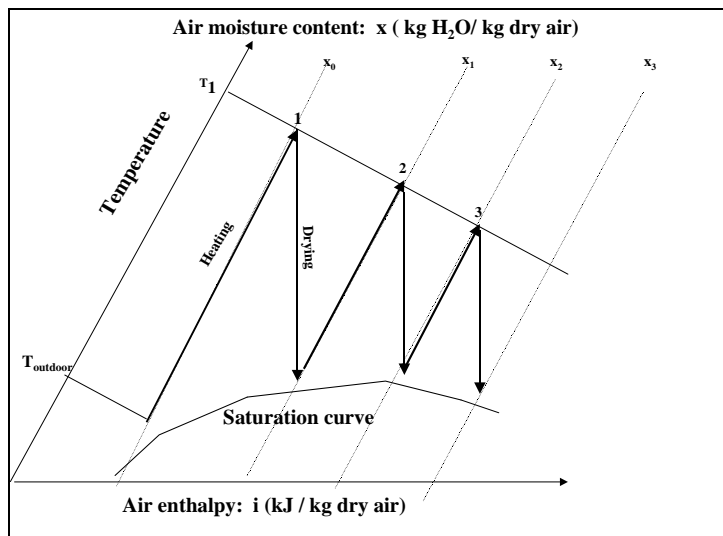
Figure 7. Comparison of one stage and multistage drying systems with the same inlet air temperatures in the Mollier (i,x)-diagram as a Salin-Soininen perspective transformation (Paper I).

3.2.2. Mass and heat balances of drying systems

The drying air mass flow for a given moist wood moisture change in a drying system can be determined by iterating or directly calculating the mass flow of drying air in the first steam-heated drying stage as long as the end -moisture from the last steam-heated drying stage is required. The moisture change of moist wood in focused drying systems fulfils the following equation:

$$\Delta \dot{m}_{H2O,tot} = \dot{m}_{da} \sum_{i=1}^{n} \Delta x_i \qquad , \tag{1}$$

where $\Delta \dot{m}_{H2O,tot}$ is the total evaporated water from the bulk flow of moist wood, $\dot{m}_{da}$ is the dry air mass flow of atmospheric drying air, n corresponds to the total number of drying stages (n= 1-4) and Δx_i is the water absorption capacity of drying air (kg_{H2O}/ dry air) in drying stage i as a function of the state of inlet and exhaust drying air resulting from the adiabatic evaporation of water.

The mass balance for the drying system is according to Equation (2):

$$\begin{aligned}
\text{Inlet} &\equiv \left[\dot{m}_{dry\,air} + \dot{m}_{H2O,\,air\,in} + \dot{m}_{wds} + \dot{m}_{wH2Oin} \right] = \\
\text{Outlet} &\equiv \left[\dot{m}_{dry\,air} + \dot{m}_{H2O,air\,out} + \dot{m}_{wds} + \dot{m}_{w'H2Oout} + \dot{m}_{wcond} \right]
\end{aligned} \qquad , \tag{2}$$

where the sum of mass flows of dry air, of water in the moist air and moist wood, and of wood dry solids in the inlet to the drying system, is equal to the sum of the values of outlet from the drying system. $\dot{m}_{wcond}$ corresponds to the possible mass flow of condensed water as a result of exhaust drying air cooling (i.e. $\dot{m}_{wcond}$ = 0 in the following calculations in Chapter 3).

3.2.3 Heat balances of drying systems

The heat balance of the drying systems is in accordance with Equation 3, when heat losses in the atmosphere are neglected:

$$\Phi_{drying\,air,in} + \Phi_{moist\,fuel,in} + \sum_{i=1}^{n} \Phi_{H,i} + \sum_{i=1}^{n} \Phi_{Ex,i} = \Phi_{drying\,air,out} + \Phi_{moist\,fuel,out} , \tag{3}$$

where $\sum_{i=1}^{n} \Phi_{H,i}$ corresponds to the sum of drying air heating before the drying stages in MSDS, $\sum_{i=1}^{n} \Phi_{Ex,i}$ corresponds to the sum of extra heating of each of the drying stages to compensate for heat losses by moist fuel heating (as stated in Papers I-III).

When heat losses are compensated for by the extra heating of drying stages $\sum_{i=1}^{n} \Phi_{Ex,i}$, the enthalpy flows of drying airflows before and after each drying stages are equal:

$$\Phi_{in} = \Phi_{out} \tag{4}$$

The enthalpy flow of the hot drying air flow Φ_{in} before each drying stage is calculated as:

$$\Phi_{in} = \sum_{i=1}^{z} \left[\dot{m}_i \, c_{p,i} \, (T_{in} - T_0) \right] + \dot{m}_{H_2O} \, \lambda_{H_2O,T_0} \qquad , \tag{5}$$

where T_{in} is the temperature of hot drying air (K), T_o is the reference temperature for heat balance (= 0.01 ^{o}C, which corresponds to the trippel point of water (Seppälä & Lampinen 1998)), $\dot{m}_i$ is a mass flow of component i in air, $c_{p,i}$ is the mean heat capacity of gas component i and $\lambda_{H2O,To}$ is the heat of water evaporation at reference temperature T_o according to the correlation mentioned in Reference (Lampinen HUT 94, 1996).

The airflow in the calculations consists of a mixture of gaseous raw Nitrogen N_2^*, O_2 and H_2O (z=3, Paper III). Raw nitrogen N_2^* consists of a mixture of N_2, Ar and CO_2 as mentioned in (Lampinen HUT 90, 1996). Also, because the amount of CO_2 in the air changes, the thermodynamic values for N_2^* are calculated using values of pure gaseous N_2 (Lampinen HUT 90, 1996).

The corresponding enthalpy of exhaust drying airflow Φ_{out} after each single drying stage at outlet temperature T_{out} is calculated as:

$$\Phi_{out} = \sum_{i=1}^{z}\left[\dot{m}_i\, c_{p,i}\, (T_{out} - T_o)\right] + (\dot{m}_{H_2O} + \Delta\dot{m}_{H_2O})\, \lambda_{H_2O,T_o} \qquad , \qquad (6)$$

where $\Delta\dot{m}_{H_2O}$ is the evaporated water mass flow in a single drying stage.

In Equation (6), the outlet temperature of exhaust drying air T_{out} is determined by the set temperature difference to the adiabatic saturation temperature T_s of the entering hot drying air at temperature T_{in}. In Equations (5) and (6), the existing mean heat capacity $c_{p,i}$ for a single air component i is calculated as an average value between temperatures T and T_o following (Hougen et al. 1954).

3.2.4 Specific energy consumption of wood drying

The specific energy consumption of wood drying in different drying systems is determined as in Papers I-III, in which it is seen as a relation of total heat input to the drying system to the mass flow of evaporated water (Pakowski & Mujumdar 1987):

$$SEC = \sum_{i=1}^{n}(\Delta\Phi + \Phi_{Ex})_i \Big/ \sum_{i=1}^{n}\Delta\dot{m}_{H20,i} \qquad , \qquad (7)$$

where $\Delta\Phi$ is the heat flow for heating drying air before drying stage i , Φ_{EX} is extra heat flow needed to compensate for moist fuel heating to drying temperature T_s (evaporation of water occurs at temperature T_s) to keep the drying action adiabatic in respect to the drying air, and $\sum_{i=1}^{n}\Delta\dot{m}_{H_2O,i}$ is the total evaporated water mass flow from fuel.

3.2.5 Thermal and evaporation efficiencies of wood drying operations

The thermal efficiency η_{th} of the drying operation is given as the relation of heat consumption of water evaporation to total heat consumption of the drying system (Papers I-III):

$$\eta_{th} = \sum_{i=1}^{n} \left(\Delta \dot{m}_{H_2O,i} \; \lambda(t_{s,i}) \right) 100 / (\Phi_{Tot}) \qquad , \qquad (8)$$

where $\Delta \dot{m}_{H_2O,i}$ is the mass flow of evaporated water in dryer i, $\lambda(t_{s,i})$ is the heat of water evaporation in drying stage i at saturation temperature $t_{s,i}$ and Φ_{Total} is the total heat consumption (i.e. input) of the drying system.

In this work, evaporation efficiency η_{Evp} for a single drying stage is defined as:

$$\eta_{Evp} = (t_{g,in} - \Delta t_{gc}\text{-}t_{out}) \; 100 / (t_{g,in} - t_s) \qquad , \qquad (9)$$

where $t_{g,in}$ is the drying air temperature at the inlet to the drying stage, Δt_{gc} is the hot drying air cooling before the start of water evaporation as a result of initial heating of moist fuel to drying temperature t_s and t_{out} is the temperature of exhaust drying air from drying stage i.

Evaporation efficiency η_{Evp} depicts the relation of the temperature change of drying air in the drying stage, minus initial cooling as a result of wood heating to drying temperature t_s, to the total adiabatic temperature change of hot drying air from inlet temperature t_{in} down to adiabatic saturation temperature t_s.

3.3 Drying air mass flows in drying systems

In Figure 8, mass flows of drying air per evaporated water are shown as functions of feed drying air temperature and the number of drying stages in the drying system.
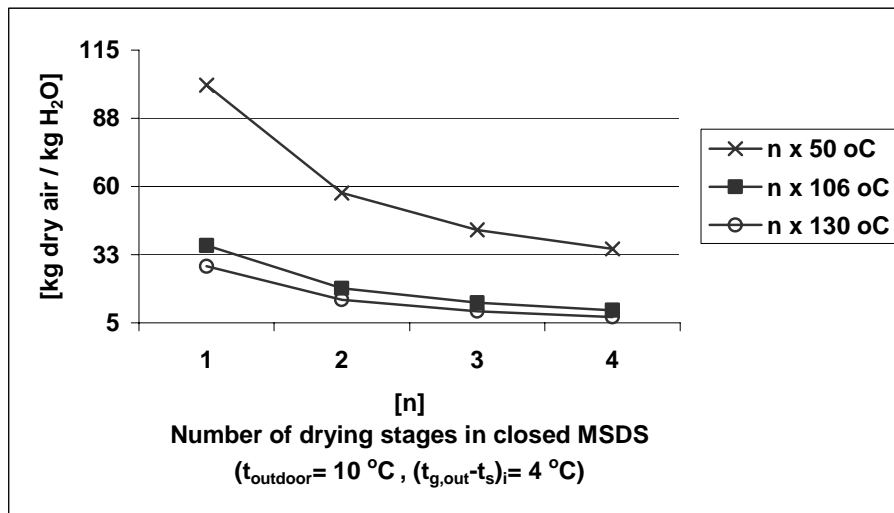
Figure 8. Dry air mass flows for the same overall extent of drying as functions of the number of drying stages and feed air temperature. Moisture change: 57.5…22 w-%$_{H2Otot}$ corresponds to moisture ratios 1.35 … 0.28 kgH2O/kg DS.

In Figure 8 the dry air mass flow is reduced by over 65 % when the number of drying stages is increased from one to four with a feed drying air temperatures of 50 ^{o}C. Furthermore, the dry air mass flow is reduced by over 92 % when one dryer system 1x

50 ^{o}C is replaced with an MSDS of 4x130 ^{o}C. In this case, the MSDS structure enables a reduction in the drying air mass flow, so dimensions and investment costs of the drying stage equipment and of air ducts are also reduced. In reality the availability of the drying process, the internal power consumption of the process equipment and both the thermal parameters and stability of the material to be dried are the main parameters for specifying a sensible number of dryers in MSDSs (Papers I-III).

3.4 Specific energy consumption and evaporation efficiency of wood drying operations

In Figure 9 the specific energy consumption (SEC) of the drying system is shown as a function of the number of drying stages and the temperature of feed drying air in those drying stages.
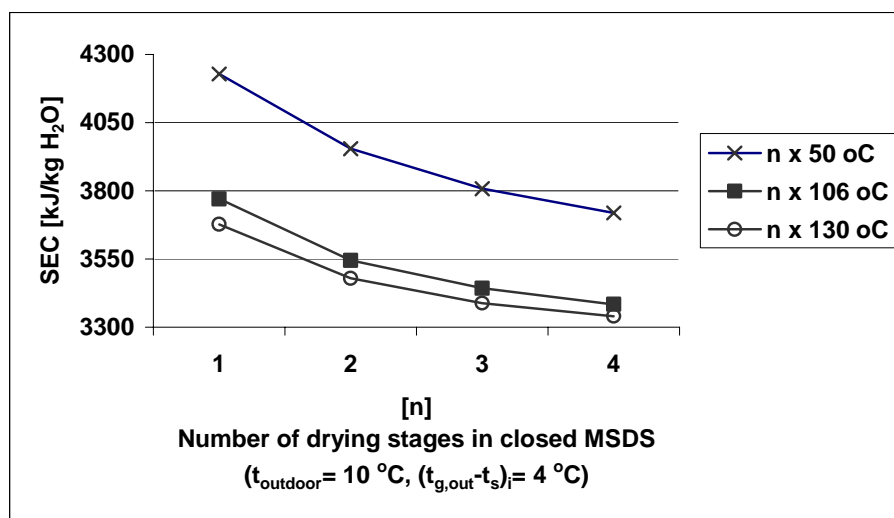
Figure 9. Specific energy consumptions (SEC) for the same overall extent of wood drying as a function of the number of drying stages and feed air temperature. Moisture change: 57.5 … 22 w-%$_{H2Otot}$ (1.35 … 0.28 kgH$_2$O/kg DS).

In Figure 9 the SEC of wood drying is reduced by around 12 % when the number of drying stages is increased from one to four with a feed drying air temperature of 50 ^{o}C. Furthermore, the SEC of drying is reduced by around 21 % when one dryer system 1x 50 ^{o}C is replaced with an MSDS of 4x130 ^{o}C.

Figure 10 shows the influence of outdoor air temperature (values for ($t_{g,,out}$-t_s)$_i$ are set equal in all drying stages) on SEC values of closed multistage drying systems (two drying stages). It also shows that the SEC value of an MSDS (2x50 ^{o}C) decreases by 40 % when the outdoor temperature increases from –15 ^{o}C to +15 ^{o}C, whereas, the SEC value of an MSDS (2x130 ^{o}C) decreases by around 23.5 %. In calculations for SEC values at outdoor temperatures below 0 ^{o}C, ice warming and melting at 0 ^{o}C is taken into account. All moisture in the wood is assumed to be frozen, as mentioned in Papers I-III. It can also be seen that the SEC value of a drying operation at an outdoor temperature of –15 ^{o}C decreases by 27.6 % when an MSDS (2x50 ^{o}C) is replaced with an MSDS (2x130 ^{o}C). At an outdoor temperature of +15 ^{o}C, the SEC of drying decreases by 6.7 % when an MSDS(2x50 ^{o}C) is replaced with an MSDS (2x130 ^{o}C).
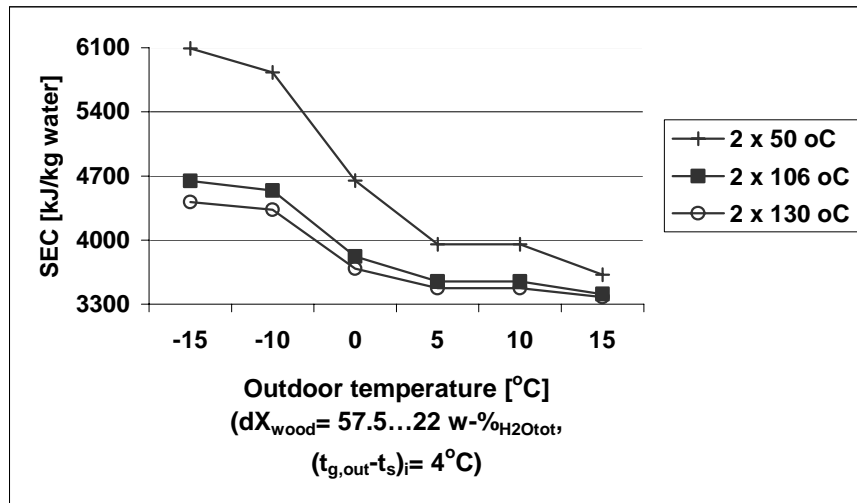
Figure 10. Influences of outdoor temperature and inlet drying air temperatures on the SEC of closed MSDS structures, consisting of two drying stages.

From Figure 3 of Paper I the SEC values of specified MSDSs, shown as a function of the exhaust drying air temperature difference of the drying system to 100% saturation temperatures ($(t_{g,out}-t_s)_i$), can be read using the following 'rules of thumb':

1 . The SEC of the drying operation decreases as the inlet temperature of drying air increases.

2. It decreases as the number of drying stages increases with constant drying air feed temperatures in the drying stages.

3. It increases slightly, the higher the drying air feed temperatures in the drying stages, and the higher the number of drying stages in the MSDS, despite the difference between the drying air temperature and the full saturation state increasing in the drying stages (between values $(t_{gout}-t_s)$= 4-20 ^{o}C).

In Figure 11 the SEC values of MSDSs (i.e. structure 2H) are shown as functions of different wood drying sequences (i.e. wood moisture changes in MSDS) and drying air inlet temperatures in the drying stages. From Figure 11 it can be seen that the greater the amount of wood being dried in MSDS, the lower the SEC value of wood drying.
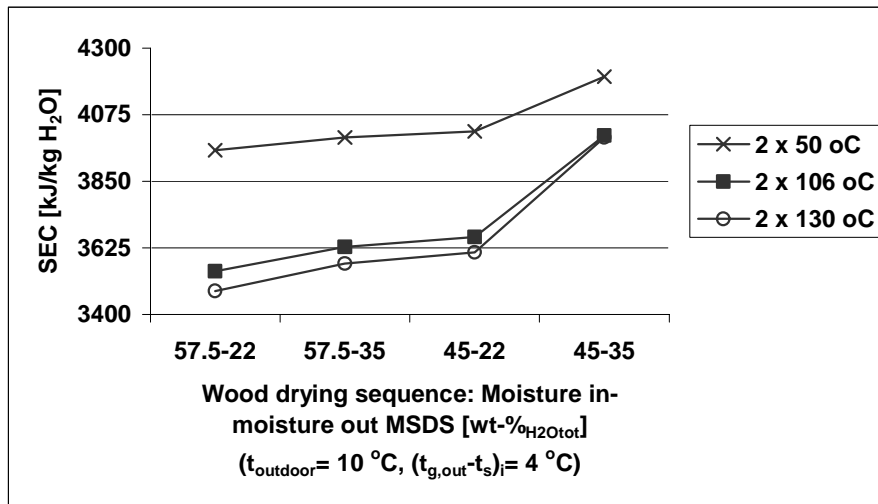
Figure 11. Specific energy consumption of MSDSs consisting of two pieces drying stages, as functions of the wood drying sequence (i.e. moisture changes) in MSDSs and of drying air inlet temperature. Equal mass flows of wood dry solids in MSDS.

3.5 Thermal and evaporation efficiencies of wood drying operations

It can be speculated with regard to the thermal efficiency of wood drying in MSDSs that the lower the SEC value, the higher the thermal efficiency η_{th}. In Figure 12 the corresponding thermal efficiencies of wood drying operations in MSDSs (i.e. a structure of 2H) are shown as functions of outdoor temperatures and of drying air inlet temperatures in the drying stages.
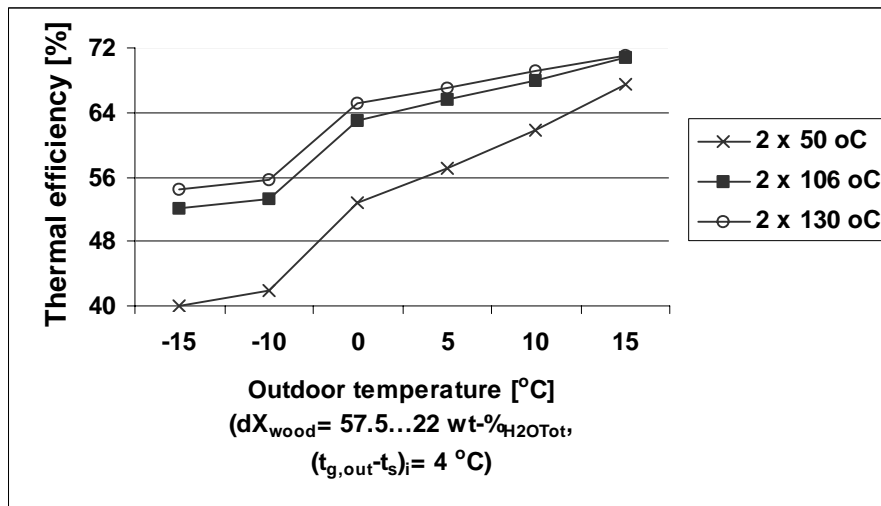
Figure 12. Influences of outdoor temperature and of inlet drying air temperatures on the thermal efficiency of wood drying operations in closed MSDS structures (consisting of two drying stages).

Figures 10 and 12 confirm the speculation above that the higher the thermal efficiency, the lower the SEC value of the wood drying process. At outdoor temperatures below 0 ^{o}C, ice melting reduces the thermal efficiency of the wood drying operation.

In Figure 13 the thermal efficiencies of single drying stages, and of total drying systems in equivalent closed MSDS structures consisting of four drying stages are shown as functions of outdoor air temperature.
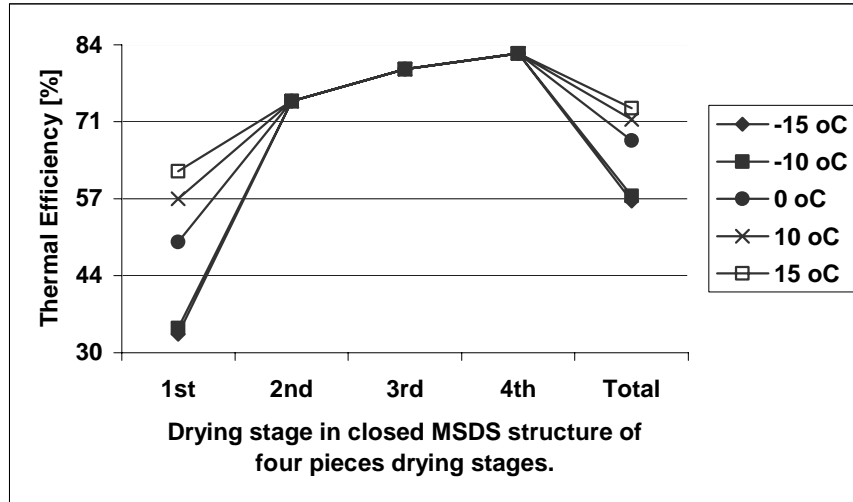
Figure 13. Thermal efficiencies of single drying stages, and of the total wood drying process in a selected closed MSDS structure with four drying stages as a function of outdoor air temperature.

From Figure 13 it can be speculated that if the thermal heating of the first drying stage varies according to outdoor temperature changes (i.e. snow and ice melting in wintertime), the control and operation of the total MSDS can be quite stable and uncomplicated. As can be seen, the last drying stages 2-4 operate equally at outdoor temperatures ranging from −15 to +15 ^{o}C if the heating and control of the first drying stage confirms the required moisture reduction of the wood. The thermal efficiency of the first drying stage has an influence on the total thermal efficiency of the MSDS.

Finally, Figure 14 shows the thermal efficiencies of equal drying operations and so-called evaporation efficiencies in single drying stages as functions of outdoor temperature. It can be seen from Figure 14 that evaporation efficiency η_{Evp} (Evap eff) is near the thermal efficiency η_{th} (Th eff) in the last drying stages in closed MSDS structures, where the energy required to heat the wood to the drying temperature $t_{s,i}$ is less than in the first drying stage. The evaporation efficiency of drying takes into account the initial cooling of the hot drying air stream because of the initial heating up of wood particles to the drying temperature. The thermal efficiency takes into account the relation of evaporation heat demand to heat demand of drying air preheating (or total heat input) before the single drying stage. The thermal efficiency is better for analysing total process efficiency, whereas evaporation efficiency is better for the purpose of analysing the single drying stage operation. Dimensionless parameters, such as capacity factor, Stanton number and a modified Stanton number, as mentioned in (Wang & Chen 2000), can be applied as effective tools in sophisticated MSDS process and single drying stage designs.
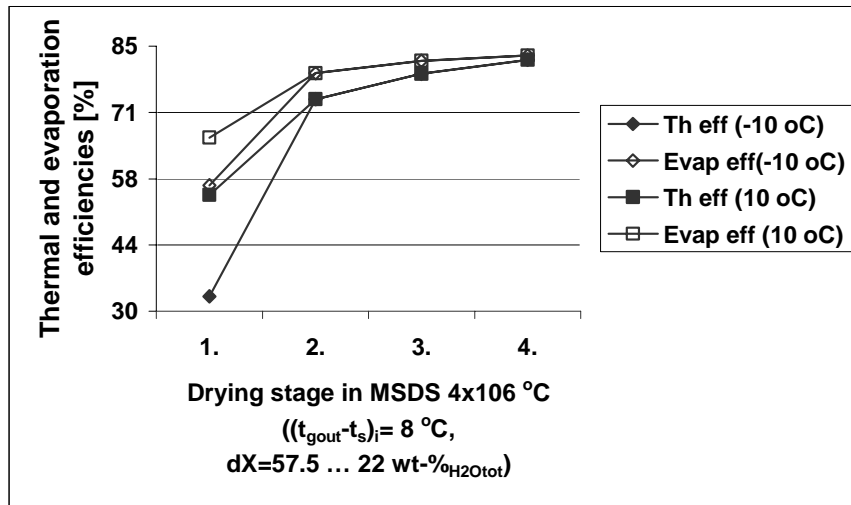
Figure 14. Comparison of thermal efficiencies (Th eff) and of evaporation efficiencies (Evap eff) of single drying stages in an MSDS of structure of 4x106 ^{o}C drying stages as functions of outdoor air temperature.

In Figure 14 the total heat consumption for initial heating of the wood bulk flows before drying in each drying stage amounts to 8.5 % (at an outdoor temperature of +10 ^{o}C) and nearly 20 % (at an outdoor temperature of –10 ^{o}C) of total heat consumption in MSDSs. Heat demand for ice melting in wintertime reduces both thermal and evaporation efficiencies.

4 INTEGRATED DRYING AND BOILER-PLANT SYSTEMS

The process descriptions and performance data of integrated drying and boiler-plant systems are given in Papers I-V. Mass and heat balances of CHP plant boilers and of MSDSs are linked together with a third calculation file for the steam system of CHP plants. The MSDS calculation file includes four types of heat transfer equipment: convective drying air heater, convective drying air cooler, condensing scrubber (i.e. exhaust drying air cooling unit) and scrubber circulation water convective cooler. The mass and heat balances of the CHP plant boiler (regarded as a bubbling fluidised bed boiler, BFBB) are divided into two parts: a cooled furnace and convection part. Radiation losses from the CHP plant boiler into the atmosphere are taken into account, whereas heat losses from the MSDS into the atmosphere can be neglected (i.e. they are very small) if the drying equipment in the MSDS is well insulated (Papers II-III).

4.1 Integrated drying and boiler-plant systems

The calculation for power and heat production of total drying and boiler-plant systems is performed according to Equations (10-12) following. Exhaust drying air from the MSDS is led into the combustion stage of CHP plant boiler as part of the total combustion air. For heat produced as live steam Φ_{LS} from a CHP plant boiler, the following is valid:

$$\Phi_{LS} = \eta_{Boiler} \left(\dot{m}_{f, fin} \, q_{iw,fin} \right) > \eta_{Boiler,o} \left(\dot{m}_{f,o} \, q_{iw,o} \right) \quad , \tag{10}$$

where η_{Boiler} is boiler efficiency (= steam effect/fuel input), $\dot{m}_f$ is the mass flow of moist fuel mixture of wood and peat, sub-index o corresponds to the original moist fuel without wood drying, sub-index fin corresponds to the fuel mixture of peat and wood after wood drying and q_{iw} represents the corresponding effective heating value of moist wood.

Boiler efficiency η_{Boiler} in Equation (10) is calculated from the heat balance of the CHP plant boiler, shown in (Lampinen 1996, HUT 90). Effective heating values (q_{iw}) in Equation (10) are calculated according to (Lampinen 1996, HUT 90), which refers to equations for calculating the effective heating value of different solids fuels and peat shown in (Raiko et al. 1995). In the calculation of moist wood and moist peat effective heating values, the average initial compositions for wood and peat (shown in Attachment A) in Finland are used according to (Rautanen 2000, Alakangas et al. 1987, Lampinen 1996 HUT 90).

Net power and heat production $\Phi_{CHP,out}$ in integrated drying and boiler-plant systems is calculated from the following total function with given steam pressures (i.e. extraction and backpressure steam) in CHP plant steam systems in Papers II-III:

$$\Phi_{CHP,out} = \text{Function} \left(\Phi_{LS}, \eta_{hp}, \eta_{lp}, \eta_{gen}, \Phi_{IHCtot}, \Phi_{IPC,tot} \right) \quad , \, (\text{MW}_{th+e}) \tag{11}$$

where net output CHP value $\Phi_{CHP,out}$ ($\Phi_{th} + \Phi_e$) is a function of heat flow in live steam, $\eta_{hp,lp}$ are isentropic efficiencies of high and low pressure parts of the steam

turbine, Φ_{IHCtot} is total internal heat consumption of the process equipment in integrated drying and boiler-plant systems and $\Phi_{IPC,tot}$ is total internal power consumption of the main process equipment in integrated drying and boiler-plant systems.

CHP efficiencies for net output power, for net heat for use of integrated pulp and paper mills and for total net output CHP are calculated in each case in relation to fuel input in CHP plant boilers:

$$\text{CHP efficiency} = \frac{(\text{Net output value (power or heat or CHP))} 100}{(\dot{m}_f \; q_{iw})} \qquad (12)$$

Because moist wood is dried outside the furnace of a CHP plant boiler, the total flue gas mass flow from combustion is less than in CHP plant boilers without an MSDS connection. As a result of an MSDS connection to a CHP plant boiler, an increase of dry solids capacity to combustion is possible. Also, with existing CHP plant boilers (i.e. with the modernization of these CHP plants), the total flue gas mass flow from combustion can be increased to a degree without overly increasing the flue gas pressure drop in the convective section of the CHP plant boiler (Arhippainen 2000, Paper IV). An increase in the solid burning capacity of a CHP plant boiler increases the total net CHP output values $\Phi_{CHP,out}$ as in Equation (11).

The optimization task for increasing CHP-output values from integrated drying and boiler-plant systems has several sub-considerations, such as: 1. Maximizing wood drying kinetics (i.e. decreasing total drying time); 2. Optimising drying air feed temperatures in drying stages in MSDS; 3. Choosing heating agents for drying air pre-heating (i.e. decreasing primary energy consumption); 4. The possibility to add different fuel mixtures or mixing fuels into the dried wood mass flow from the MSDS before feeding into the CHP plant boiler (i.e. increasing the capacity of the CHP plant boiler); 5. Decreasing organic emissions from integrated drying and boiler-plant systems in flue gases (i.e. unburned organic) and in condensed water.

4.1.1 Internal heat consumption of integrated drying and boiler-plant systems

The calculated internal heat consumption value Φ_{IHCtot} of integrated drying and boiler-plant systems includes combustion air pre-heating (combination of indirect heating with flue gases from the CHP plant boiler and backpressure steam), soot blowing in the CHP plant boiler (see Table 2), direct heating of the feed water tank (FWT) with backpressure steam, heating and melting ice in wood and peat in wintertime with secondary process energy (i.e. hot condensate flow), secondary process energy for heating drying air in the drying stage heated by secondary energy, as well as backpressure and extraction steam for heating drying air in the steam-heated drying stages.

In Table 2 the heat demand of soot blowing (i.e. with extraction steam) is shown as a function of the steam effect of the CHP plant boiler (i.e. BFBB). The heat consumption of soot blowing in a CHP plant boiler is calculated according to a linear equation as a function of the steam effect of the CHP plant boiler according to the values shown in Table 2.

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Table 2. Heat consumption of soot blowing of BFBB as a function of steam effect (Rantee & Hopia 2000).

Steam effect of FBB [MW$_{th}$]	Extraction steam for soot blowing [1000 kg/24 h]
100	15-20
200	20-35
300	35-50

4.1.2 Internal power consumption of the CHP plant process

The calculated internal power consumption value $\Phi_{IPC,tot}$ for the integrated drying and boiler-plant systems takes into account the following main process equipment: combustion air and flue gas fans (one of each), a feed water pump, a condensate pump from integrated pulp and paper mills to the feed water tank (FWT), a secondary process energy (condensate) pump for feed in the MSDS and CHP plant and return to the pulp mill, the main fuel feed equipment to the CHP plant boiler (separate main lines for wood and for peat)[1], an electrostatic precipitator (three separation fields), fuel transport and feed equipment for each drying stage, between each drying stage and from the last drying stage in the MSDS to the main wood feed line to the CHP plant boiler, a drying air fan for the drying stage heated by secondary energy, drying air fans for the steam-heated drying stages (one fan per steam-heated drying stage), an exhaust drying air cooling unit (i.e. a packed scrubber, which causes increased power consumption of combustion air fan), a re-circulation water pump for the cooling unit, a re-circulation water cooler for the cooling unit (indirect cooling with cold water in the cooling system) and a cooling water pump in the cooler.

Calculations for $\Phi_{IPC,tot}$ values of CHP plant boiler process equipment does not include process instrumentation, control room equipment, CHP plant boiler ash-discharge equipment and fuel transport/loading equipment to fuel feed lines of the CHP plant boiler and MSDS.

The $\Phi_{IPC,tot}$ values are calculated according to equations or data shown in References (Lampinen 1997, Gullichsen et al. 1999, Nokian ilmastointi 198x, Kuivas 2000, Reyes 1997, Nyman ed. 1973). The calculated IPC value for a CHP plant boiler only has the value of about 18.6 kW$_e$/MW$_{steam\ effect}$[2]. Detected Φ_{IPC} values of fluidized boilers in power plant projects have been detected to be between values of 20-30 kW$_e$/MW$_{steam\ effect}$ (Kaskela 2000).

In one process calculation the $\Phi_{IPC,tot}$ value of the whole system of integrated drying and boiler-plant systems was in an order of magnitude 20.3 kW$_e$ /MW$_{steam\ effect}$ (of the CHP plant boiler), which corresponds to a value of 2 % of steam effect of the CHP plant boiler or 1.75 % of the fuel input into the CHP plant boiler, when heat losses from the total fuel input in flue gases are 7.5 % and radiation losses into the atmosphere are 1.5 %. In the Technology Development Centre in Finland (TEKES 2000) bulletin, CHP plant installation without a moist fuel drying system has an IPC value of 2.6 % from the fuel input (heat losses of 1.5 % as radiation losses into the atmosphere and of

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[1] Lengths of main lines are 200 m each.
[2] The CHP plant calculation takes in account pressure drops for flue gases in the stack (height of 70 m, natural draught is noted) and in the flue gas duct (total length of 150 m).

10 % into flue gases from the total fuel input (i.e. fuel input) into the CHP plant boiler. The order of magnitude of IPC values for the calculated integrated drying and boiler-plant systems is suggested to be satisfactory in calculating changes in output power production values after installation of different MSDSs, when compared to a CHP plant boiler without moist wood drying system.

4.1.3 Corrections to results given in Papers I-IV

The results given in Papers I-IV contain the following inaccuracies, which are hereby corrected as follows:
1. The combustion stage heat balance of the CHP plant boiler contained an error in programming coding that resulted in the boiler efficiency shown in Paper III being too high. The corrected boiler efficiency given in the example in Paper III should be 94.3 % instead of 94.9 % (Paper III, p. 72).
2. Steam system: calculated net heat values for integrated pulp and paper mills have values in orders of magnitude 4-7 %, higher than reported earlier in Papers II-IV. An error in programming produced a false value for the enthalpy of condensate water mass flow from MSDSs to integrated pulp and paper mills.
3. Shaft power of drying air fans: a error in programming of Ergun equations in the Excel-calculation for air side pressure drops in wood-based biomass beds in drying stages gave values that were too high. However, in practice these errors had a negligible effect on the result (i.e. errors in orders of magnitude of units [kW$_e$] against reported net output power values in units of [MW$_e$]).

4.2 Wood drying kinetics

The calculation for MSDS mass and heat balances also includes calculations of the wood drying kinetics according to a simplified calculation procedure for wood particles that are regarded as spheres (Paper III). In this calculation the drying phenomen occurs in drying stages of direct contact and of fixed bed mode (i.e. no fluidisation of wood particles). The fixed bed mode was selected because of the moderate internal electric power consumption values [kW$_e$] of single drying air fans. The wood drying kinetics are calculated for pre-design and estimation purposes only. The calculation of wood drying kinetics uses many simplifications: the drying phenomen occurs at constant temperature t_s, the heat conductivity of moist wood is ∞ and capillary forces of wood are expected to be able to keep the moisture distribution of wood particles (i.e. spheres) equal in drying down to the moisture content of the wood's FSP (fibre saturation point). Heat transfer is assumed to happen as convective heat transfers between the air and the outer surface areas of the particles (Paper III). The particles are not expected to shrink during water evaporation. Convective heat transfer coefficients α in single drying stages are calculated from an equation including a Nusselt number, which is applied to wood spheres (Ranz & Marshall 1952, Paper III).

The drying phenomen of wood particles in a single drying stage of a continuous drying system is divided into two stages as shown in References (Brammer & Bidgewater 1999, Williams-Gardner 1971): first, the initial heating of particles to the adiabatic saturation temperature (T_s) of entering hot drying air occurs. During that period, no drying of particles occurs. After the initial heating of particles, the constant rate drying of particles starts at constant temperature T_s. The total wood drying time in

the MSDS from initial moisture content down to outlet moisture content at the minimum fibre saturation point (FSP) of the wood is determined as a sum:

$$\tau_{Tot} = \sum_{i=1}^{n} (\tau_h + \tau_d)_i \qquad , \qquad (13)$$

where sub-index h corresponds to initial heating and sub-index d corresponds to the constant rate drying time of the wood particle from the initial moisture content to the outlet moisture content.

According to (Brammer & Bridgewater 1999), with certain materials, a constant rate period of drying may not be observed at all, except in very high initial moisture contents, whereas with other materials, constant rate drying continues to very low values under FSP (or critical) moisture content. Because wood-based biomasses are numerous, a lot of empirical tests with different wood-based biomasses are necessary for reliable modelling of drying kinetics.

4.3 Results for integrated drying and boiler-plant systems

4.3.1 Calculated results for power and heat production values

As reported in Papers II-IV, the installation of MSDSs in CHP plant boilers increases the power production. The lower the wood's final moisture content from the MSDS, the greater the power increase. The net heat for integrated pulp and paper mills in the steam system decreases, unless the secondary process energy is used for wood drying in the MSDS. When secondary process energy is utilized for wood drying, this amount of secondary energy can be transferred directly to the fuel input growth of the CHP plant boiler, as reported in Papers II-IV. With considerable secondary process energy utilization in wood drying, the net heat for integrated pulp and paper mills remains equal to that of CHP plant boilers without MSDS installation, even with a high degree of wood drying down to the FSP moisture content. But the higher the secondary energy drying efficiency, the lower the net output power production, because of the increased drying air fan power resulting from the high mass flow of drying air (i.e. poor water absorption capacity of low-temperature drying air).

Figure 15 shows the CHP efficiencies (power or heat or power+heat production values/ fuel input) of CHP plants without moist wood drying and as a function of MSDS operation. From Figure15 it can be seen, that a CHP plant without MSDS installation has the highest CHP efficiency because wood drying in MSDSs consumes heat and power. CHP plants with minor wood drying in the MSDS have a higher CHP efficiency than CHP plants with a high degree of wood drying in MSDSs. This is because of the lower internal heat and power consumption values. Separate calculations have shown that an increase of dry solids in combustion raises the heat production efficiency with a similar wood drying sequence in MSDSs.
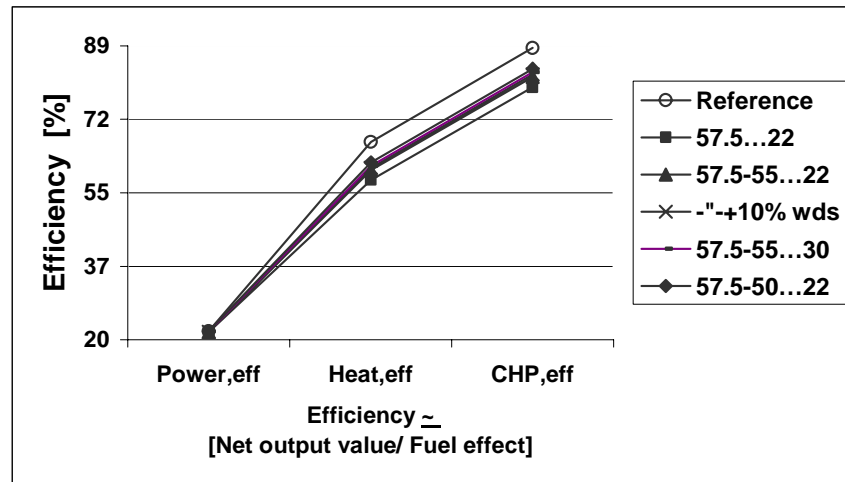
Figure 15. CHP efficiencies (for corresponding net values) of different CHP plants as functions of the wood drying sequence in MSDS. One sequence (i.e. 57.5-55…22 wt-%$_{H2Otot}$) also includes a ds increase of 10 % as wood in combustion. The fuels in CHP plant boilers are wood and peat [48 wt-%$_{H2Otot}$] .

4.3.2 Influences of wood drying in selected CHP plant

Tables 3 and 4 show output CHP values and flue gas mass flows from combustion in selected CHP plants with and without MSDS connection.

Table 3. CHP output net values and flue gas mass flows from combustion as a function of the operation principle of selected integrated drying (i.e. structure of S+2H) and boiler-plant boiler systems. T$_{outdoor}$ is 10 ^{o}C and combustion's excess-air factor λ in all points is 1.2. Fuels: Wood: Wood drying sequence in MSDS: 57.5-55…22 wt-%$_{H2Otot}$. Peat: Moisture content of peat is 48 wt-%$_{H2Otot}$.

CHP plant	Power net [MW$_e$]	[+/-% to reference]	Heat net [MW$_{th}$]	[+/- % to reference]	Flue gas [kg/s]	[+/-% to reference]
Reference	37.1	-	111.8	-	103.5	-
+ MSDS	40.0	7.8	109.3	-2.2	100.3	-3.1
-"-+10%DS	43.2	16.5	119.1	6.5	110.5	6.8

From Table 3 the benefits of MSDS installation in a CHP plant boiler can be listed as follows:
1. **Equal wood dry solid in combustion:** increase in net output power production only. Decreases in net heat production and in flue gas mass flow, when compared to reference states. If secondary energy heat is utilized sufficiently in wood drying, an increase in net heat production can also be achieved, as shown in Papers II-III.
2. **Increase of dry solids in combustion (as wood):** increase in both power and heat generation. A decrease in the excess-air factor of combustion and utilization of secondary process energy in drying (i.e. with exhaust drying air out-purge) increases CHP output values and decreases the mass of flue gases from combustion, which enables simultaneous increases in both power and heat production with a smaller increase in dry solids in the selected CHP plant boiler than is shown in Table 3.

In Table 4 the corresponding live steam mass flows and heat losses in flue gases of a CHP plant boiler (as in Table 3) are shown against the total fuel input in the CHP plant boiler with and without MSDS installations. The process values of the selected CHP plant boiler are listed in Papers II-III. From Table 4, it can be seen that wood drying in the MSDS both increases live steam production of the CHP plant boiler and decreases the relative value of flue gas losses from total fuel input as a result of wood pre-drying outside the furnace of the CHP plant boiler. An MSDS connection in a CHP plant boiler enables capacity increase, which raises live steam production even more.

Table 4. Live steam production of a CHP plant boiler (90 bar(A), 525 $^{\circ}$C) and heat losses in flue gases (i.e. enthalpy flow of flue gases after Luvo) as a function of selected CHP plant processes. CHP plant processes similar to those in Table 3.

| CHP plant operation	Live steam production [kg/s]	Heat losses in flue gases of total fuel input [%]
Reference	57.5	8.6
+ MSDS	63.6	7.5
+ MSDS + 10% DS	68.6	7.7

4.3.3 Ratio of net power to net heat in the selected CHP plant

The power-to-heat ratio of the selected wood and peat combusting integrated drying and boiler-plant systems depends on available secondary process energy flows, the moist biofuel drying rate and existing process equipment in both integrated systems (Paper IV). The possibility of increasing the solids burning capacity of the combustor benefits both power and heat production. An increase in power production only is enough when the process heat demand of the integrated pulp and paper mill decreases due to the closure of pulp and paper making processes (Paper IV). In Figure 16, the calculated power-to-heat ratios of the reference CHP plant and of selected integrated drying and boiler-plant systems are shown as a function of the wood's final moisture content from constant MSDS structures with equal process parameters (e.g. outdoor air temperature, (tgout-ts)$_i$ in drying stages and diameter of wood).

It can be seen from Figure 16 that MSDS installation in CHP plants raises the power-to-heat ratio of CHP plants compared to the reference CHP plant because of the heat consumption of MSDSs. The more the wood is dried in the MSDSs, the greater the increase in the power-to-heat ratio of the CHP plants. Installations of internal heat recovery units (i.e. heat recovery from exhaust drying air from the drying stage heated by secondary energy and/or from the cooling unit of exhaust drying air from the MSDS, as described in Papers II-IV) have an influence on the calculated power-to-heat ratio of integrated drying and boiler-plant systems. The ratio of net power to net heat selected CHP plants exceeds a value of 0.4 only when the CHP plant boiler has an MSDS connection, but not combustion air pre-heating partly with flue gases (i.e. in luvo) in addition to backpressure steam. Also, when the heat recovery rate from flue gas flow for preheating combustion air in the CHP plant boiler is reduced (i.e. increase in internal heat consumption of drying and boiler-plant systems), the calculated ratios of net power-to net heat could take the values shown in Paper IV. The reduced heat recovery means that the temperature of flue gases after combustion air pre-heating (i.e. luvo) exceeds 120 $^{\circ}$C, which is given in Papers II-III (i.e. process values for CHP plant boiler and steam system).

The distribution of backpressure and extraction steam for wood drying in selected CHP plants has a slight influence on the power-to-heat ratio. In Papers II-IV the MSDS process with an increasing temperature profile (i.e. backpressure steam in the first steam-heated drying stage and extracted steam in the last steam-heated drying stages in MSDSs) has been described. The temperature profile can also be the reverse (i.e. decreasing), which may help produce higher ratios of net power to net heat with a higher number of steam-heated drying stages in the MSDS (i.e. four stages) than in CHP plants with MSDS systems using rising temperature profiles in steam staging for drying air heating.

It is also possible to use backpressure steam only in the MSDS for wood drying, but this option does not fulfil this thesis' MSDS design criterion that all exhaust drying air from steam-heated drying stages has to be drawn into the combustion unit along with total combustion air, without installation of an exhaust air cooling and water condensing unit, when the MSDS system contains only two steam-heated drying stages (i.e. MSDS structure of 2H or S+2H). Also, different staged drying air pre-heatings before each drying stages in the MSDS with secondary process energy flow, backpressure and extraction steam may offer opportunities to control the ratio of net output power to net output heat in CHP plants, but the exploration of this possibility will be left to post-doctoral development work relating to MSDSs.
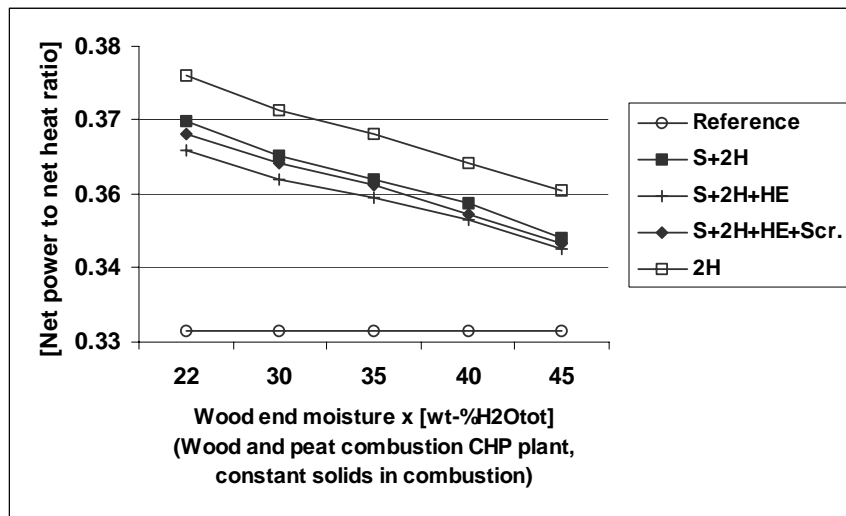
Figure 16. Corrected values for the ratios of net output power-to-net output heat of selected CHP plant shown as functions of final wood moisture content and of the structure of the MSDS, which consists of one drying stage heated by secondary energy and two steam heated-drying stages (Paper IV).

4.3.4 Internal power consumption of the CHP plant process

In Figure 17 the corrected distribution of internal power consumption of the main process equipment in selected integrated drying (S+2H) and boiler-plant systems is shown after the corrections mentioned in Chapter 4.1.3. In Figure 17 the values for the internal power consumption of the main process equipment in the integrated drying and boiler-plant systems are shown as functions of the drying air slip velocity (i.e. drying air

velocity in fixed bed operation mode through a cross-section area of the drying stage) and of the wood moisture content change (i.e. drying sequence) in MSDSs.
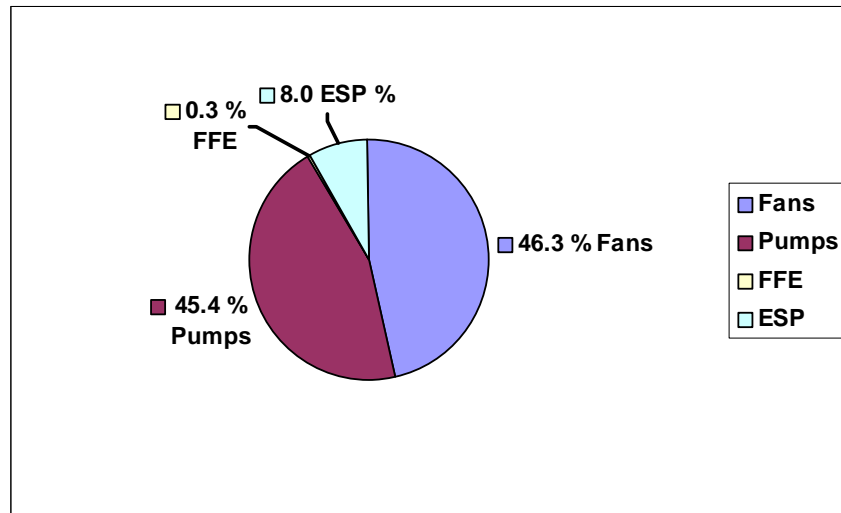
Figure 17. The corrected distribution of the internal power consumption of the main process equipment in integrated drying and boiler-plant systems. (Paper III).

In Figure 18, the internal power consumption value of the integrated drying and boiler-plant systems is shown to be in the order of magnitude of 20 kW_e/MW steam effect of CHP plant boilers (i.e. 2 % of the steam effect of the CHP plant boiler) when the MSDS has a structure of S+2H. The internal power consumption value of selected integrated systems (CHP plant boiler + MSDS) decreases by almost 3.5 % as the number of steam-heated drying stages increases from two to four. This is a result of the decrease in drying air mass flow. The internal power consumption value is thus fairly constant, because a reduction in the exhaust drying air mass flow from an MSDS has an influence on the mass flow of atmospheric combustion air in a CHP plant boiler (i.e. the power consumption of the total combustion air fan remains fairly stable and constant). Changes in outdoor air temperatures have a greater influence on the heat consumption value of MSDSs (i.e. the SEC value of the wood drying process greatly increases as a result of snow and ice melting, as reported in Paper III).
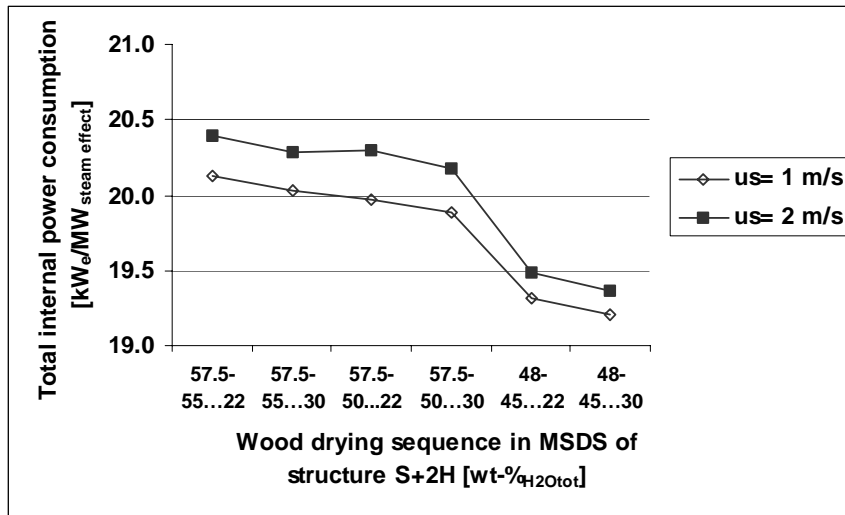
Figure 18. Internal power consumption values of integrated drying and boiler-plant systems as functions of drying air velocity through a cross-sectional area of the drying stage (i.e. the slip velocity us in fixed bed operation mode), and of the reduction in wood moisture content. The mass flows of wood dry solids are similar. Process parameters: $(t_{g,out}-t_s)_i$= 8+12 ^{o}C, $t_{outdoor}$= 10 ^{o}C and wood spheres of diameters 20 mm.

4.4 Wood drying kinetics

In Paper III the calculated drying times for wood spheres of different diameters are given. With the maximum change in wood moisture content (dX= 57.5-55…22 wt-%$_{H2Otot}$) in the selected CHP plant process, the calculated drying times vary within the range of 6 minutes (with a sphere diameter of 5 mm) to 85 minutes (with a sphere diameter of 30 mm). The calculated water fluxes $\dot{m}''$ in the specified drying operations reported in Paper III where quite similar to the values reported by Refs (Impola et al. 1996, Laytner et al. 1992). To reach total drying time values of under 60 minutes in real-scale continuous drying operations, the maximum diameters of wood particles in the wood bulk flow should have values of between 15 and 20 mm (corresponding to spheres).

4.5 Comparisons of steam drying plants and of multistage drying systems

It is possible to make a preliminary comparison of the specific energy consumptions of multistage drying systems (MSDS) and of direct/indirect steam drying plants when the initial and final moisture contents of moist wood are taken into account. Different steam drying plants will be competitors and alternatives to MSDS wherever the drying is applied. The benefits of MSDSs lie first and foremost in the management of organic emissions from biomass drying (Paper V). The non-condensable organic emissions from biomass drying in exhaust drying air can possibly lead to combustion in combustion air. The amounts of organically loaded condensates from MSDSs are also smaller than in direct steam drying plants for biomass drying (Paper V). Furthermore, MSDSs are beneficial in that the ability to utilize low-temperature secondary process energy in drying makes them very energy efficient.

4.5.1 Specific energy consumption (SEC) of different steam drying plants

It is profitable to use extracted steam from steam turbines as heating agents for steam dryers in power plants (Ruottu 1998). Ruottu reached the following conclusions when he compared steam dryers with flue gas dryers in moist peat drying in power plants: 1. Moist peat drying in extracted steam-heated steam dryers yields higher power production than flue gas dryers when the pressures of extracted steam have values of below 20 bar (A). Both drying methods enable equal profits in power production when the steam dryers utilize extracted steam of pressures 20-40 bar(A); 2. The heat recovery rates are lower with flue gas dryers. This difference is at a maximum with extracted steam pressures below 20 bar(A), but the difference remains constant with higher extracted steam pressures up to 40 bar(A).

Direct-contact steam dryers utilize superheated steam, whereas indirect steam dryers can operate with lower steam pressures. Heat recovery from exhaust steam flows occurs more effectively, economically and at a higher temperature level than the corresponding heat recovery of water latent heat from exhaust gases of flue gas dryers. MSDSs enable a heat recovery of 30-51 % of the total input heat at a temperature level between 37 and 50 $^{\circ}$C (i.e. more, and with a higher temperature level as the number of steam-heated drying stages increases (Paper IV)). Steam dryers utilizing superheated steam (direct and indirect) have specific energy consumption SEC values of between 1000 and 1500 kJ/kg H_2O (Wimmerstedt 1999). In bark drying tests in a fluidised bed test rig, SEC values were in the range of 4322-5490 kJ/kgH_2O (Huhtinen et al. 1988). According to Wimmerstedt, gross -values for the SEC of steam drying have the order of magnitude of 2900 kJ/kgH_2O when heat losses and heat recovery are not taken into account.

4.5.2. Comparison of SEC values of MSDSs and of steam dryers in selected CHP plants

Wood-based biomass drying in selected CHP plants in integrated pulp and paper mills is taken into account in Papers II-IV. Wood is dried in MSDSs with different drying sequences. The steam dryer utilizes extracted steam of pressures between 3.4 and 40 bar(A). The heat difference between steam and the corresponding saturated water of equal pressure is utilized in both drying methods. The exit pressure of steam from the steam turbine is corrected with an isentropic efficiency of 88 %, as described in Papers II-III. The SEC value of the steam dryer is assumed to be of a gross -value of 2900 kJ/kgH_2O according to Wimmerstedt (1999). In Table 5, different SEC values per total evaporated water mass flows (i.e. total, reduced (without secondary process energy), as backpressure and extracted steam) are shown as functions of the drying sequence and of the temperature profile of steam-heated drying stages in MSDSs.

From Table 5 it can be seen that the utilization of low-temperature secondary process energy MSDSs makes this drying method perform competitively with direct and indirect steam drying plants. When special energy consumption SEC values are given in relation to the total evaporated water (kJ/kgH_2O) in MSDSs, the extracted steam consumption in MSDS (SEC_{extr}) decreases to below the values of corresponding direct-contact steam dryers utilizing superheated steam (i.e. to below values of 1000-1500 kJ/kg). As far as the drying efficiency of the drying stage heated by secondary energy is concerned, it is possible to maximize this by producing a sufficiently large change in the

wood moisture content before final drying in the steam-heated drying stages. At the same time, the reduced specific energy consumption value SECrd (i.e. taking into account only heat consumption in backpressure and extracted steam) decreases under the given gross-heat consumption of steam dryers (i.e. 2900 kJ/kg H_2O).

Table 5. Different specific energy consumption values of MSDS as functions of MSDS structure and wood drying sequence in selected CHP plants. Process values for MSDSs: $t_{outdoor}$= 10 ^{o}C, $(t_{gout}-t_s)_i$= 8+12 ^{o}C and $u_{s,i}$= 2 m/s. [SEC]= kJ/kgH_2O. Sub-indexes for SEC values: Tot= total, rd= reduced, b-p= backpressure steam, extr= extracted steam. Note! SEC_{rd}= SEC_{b-p} + SEC_{extr}.

MSDS	Drying sequence:		SECtot	SECrd	SECb-p	SECextr
S+2H	57.5-55…22 wt-%H2Otot		3681	2778	1374	1404
S+3H			3565	2760	875	1885
S+4H		Increasing profile: 70+130+(n-1)x185 ^{o}C	3513	2753	648	2104
S+2H	57.5-50…22 wt-%H2Otot		3879	2157	1064	1093
S+3H			3795	2148	681	1467
S+4H			3758	2146	506	1639
S+2H	57.5-48…22 wt-%H2Otot		3948	1942	957	985
S+3H			3875	1936	613	1323
S+4H			3843	1936	457	1479
MSDS	Drying sequence:		SECtot	SECrd	SECb-p	SECextr
S+2H	57.5-55…22 wt-%H2Otot		3692	2781	692	2089
S+3H			3608	2766	1189	1576
S+4H		Decreasing profile: 70+185+(n-1)x130 ^{o}C	3559	2756	1477	1279
S+2H	57.5-50…22 wt-%H2Otot		3886	2157	539	1619
S+3H			3824	2149	924	1225
S+4H			3789	2144	1148	996
	57.5-48…22 wt-%H2Otot					
S+2H			3953	1941	486	1455
S+3H			3899	1935	832	1103
S+4H			3868	1931	1034	898

4.5.3 Operabilities of MSDS and of steam dryer systems

The operability of MSDSs can be secured by managing the organic emissions of wood drying in the exhaust drying air, which prevents the clogging of heat-transfer surfaces in drying air pre-heaters between steam-heated drying stages. The drying stages in MSDS also have to be equipped with mechanical particle separators, which prevent or minimize mass flows of carry-over particles in exhaust drying airflows. The management of different emissions is described in Paper V and in Chapter 5 of this thesis. Also, moist wood input and outtake to/from the drying stages have to be taken into account. The wood inputs and outtakes to/from the drying stages in MSDS should

not present the same problems as those encountered earlier with pressurized steam dryers (Wimmerstedt 1999).

4.5.4 Potentials of MSDS applications in future bioenergy production

Multistage drying systems (MSDSs) can be applied widely in the field of bioenergy. Accounts of operation experiences with the drying of biomass and other substances will be useful for designing more efficient MSDSs for CHP plants. This development work will be conducted over a long period of time. MSDS applications will enable the development of new applications of different combustor types. Future bioenergy production systems, in which MSDSs can be installed, are new applications of CHP systems (e.g. micro-CHP, combined systems), pressurised combustion and gasification systems, which are listed in (Hirvonen ed. 2002). The pre-drying of moist fuels before combustion or gasification improves the effective heating value of biofuels, stabilizes the energy production process, and reduces unburned organic emissions into the environment.

5 ORGANIC EMISSSION FROM WOOD DRYING

The estimation of organic emissions (both gaseous and in condensates) from wood-based biomass drying is a necessary preliminary process that has to be completed when considering the design and operability of MSDSs. This estimation is described in Paper V. The condensing organic compounds together with carry-over particles in exhaust drying air are regarded as a potential risk that might clog and inactivate the heat transfer surfaces of drying air heaters between drying stages. Condensing organic compounds may also condense on the surfaces of drying air ducts, as a result of which solid particles in the exhaust drying air flow from the previous drying stage may adhere to the walls of drying air ducts in MSDSs.

5.1 Literature review

A literature review in the area of organic emissions from wood-based biomass drying has been completed and is attached to Paper V of this thesis. The gaseous emissions from wood drying are divided into two main groups: 1. gaseous volatile organic compounds (VOCs) and 2. gaseous condensable volatile organic compounds (CVOC). VOCs are not regarded as harmful to the operability of MSDSs because they are emitted from wood matter into the drying air, and mixed with staged combustion air in combustion in the CHP plant boiler. The risk to the operability of MSDSs exists in the possible release of CVOCs. These might inactivate the heat transfer operations of the air heaters by blocking effects and carry-over particles. These condensable organic compounds may be transferred mostly from exhaust drying air in the condensing unit as it condenses water.

According to assumptions used in the literature, the temperatures of wood dry solids in each of the direct contact drying stages remain near the adiabatic saturation temperature of inlet hot drying air (i.e. at temperatures below 100 ^{o}C) in as far as the wood's final moisture contents correspond to the minimum FSP moisture content. VOC emissions from wood drying are reported to increase greatly as the temperatures of wood dry solids exceed 100 ^{o}C , when the final moisture contents of wood dry solids are found to correspond to moisture contents of under 10 wt-%$_{H2Otot}$ (<0.11 kg$_{H2O}$/wood ds (Su et al. 1999, Otwell et al. 2000, Munter & Bäcker 1992)). The organic emissions result from accelerated thermal degradation of wood matter and the steam distillation effect (Wastney 1994, Munter and Bäcker 1992). Reference (Arvidson and Östman 1997) reports that in temperatures of up to about 200 ^{o}C the thermal degradation of wood occurs mainly at the outer surface of wood particles, which is dehydrated, so moisture is evaporated into the drying medium.

The assumption that risky CVOCs may not cause problems for MSDS operation is based on 1. maximum drying air feed temperature between 130-185 ^{o}C in steam-heated drying stages and 2. final wood moisture contents at the minimum moisture content of wood FSP. From extractive concentrations in different wood-based biomasses, it can be concluded that bark drying might cause CVOC emissions, because of the higher ether-soluble extractive content in dry solids when compared to the extractive content in birch and pine wood dry solids (Fengel & Wegener 1984, Paper V).

VOCs released from hardwood and softwood differ in both the nature and quantity of materials involved. Hardwood VOCs are mainly degradation products from the thermal degradation of wood tissue. They include methanol and formaldehyde, which

U.S. EPA regards as HAPs, i.e. hazardous air pollutants. Softwood releases much larger quantities of VOCs, most of which are terpenes. (Cronn & Truitt 1983, Otwell et al. 2000 and Banerjee et al. 1998).

5.2 Field tests

The organic emissions (both gaseous and in condensed water) from wood drying with inlet drying air temperatures close to 100 ^{o}C were studied in a direct contact fixed bed dryer in an industrial heating centre in order to confirm that exhaust drying air could be discharged into the atmosphere at the low temperatures applied in the MSDS. The detected concentrations of organic emissions in exhaust drying air flows from the direct contact wood-based biomass drying stage with low inlet temperature air (80-100 ^{o}C) were low. Therefore, it was suggested that these emissions have no practical harmful influences on the environment (Paper V). Through the discharge of exhaust drying air from the first drying stage, a noticeable amount of water from the moist wood-based biomass can also be discharged into the atmosphere instead of the CHP plant boiler furnace. This has a decreasing effect on flue gas mass flow from the combustion unit. Secondary energy use in wood-based biomass drying before combustion increases the direct heat production of integrated drying and boiler-plant systems, because there is less demand for backpressure and extraction steam in MSDSs (Papers II -V).

5.3 Preliminary conclusions

According to literature surveys and field test results from wood-based biomass drying in an industrial dryer, two main conclusions about the pre-design phase of MSDSs can be drawn:

I. Organic emissions from wood drying do not undermine the idea of the closed MSDS structure of steam-heated drying stages as a result of inactivation of heat transfer surfaces in the air heater between the steam-heated drying stages by tacky, condensable deposits of organic compounds. This is valid for certain drying air temperatures of a maximum value between backpressure and extraction steam, i.e. temperatures between 130 and 185 ^{o}C, for certain wood-based biomass particles of effective diameter greater than 5 mm, and for a certain minimum final moisture content of wood based-biomass from MSDSs greater or equal to the corresponding FSP (Paper V).

II. The exhaust drying air from the low-temperature inlet air temperature (70-80 ^{o}C) drying stage can be discharged into the atmosphere with low environmental risks (Paper V).

These main conclusions I-II have to be confirmed by testing for the following reasons: wood-based biomass properties vary geographically and the initial properties of wood-based biomasses (i.e. initial moisture content, storage time and method) vary from one integrated pulp and paper mill or power plant to another.

Note that the present MSDS alternatives were selected with the objective of avoiding internal condensation. Other works have pointed out that condensing organic compounds may form aerosols in exhaust drying air (Wastney 1994). These aerosols may cause operational disturbances in drying air heaters. Also, condensate formations in, for example, MSDS drying air ducts may increase internal power consumption, because these condensates have to be pumped away into collection systems.

6 CONCLUSIONS

In this work, pre-design evaluations of a particular type of multistage drying system (MSDS) process and a particular application of it were undertaken. For all the aspects evaluated, positive results were obtained. The in-depth performance analyses confirmed or established the following:

1. MSDSs are significantly more efficient than the corresponding single-stage dryers.

2. In comparison with the corresponding single-stage dryers, lower drying temperatures and lower air flow rates can be employed in MSDSs.

3. A lower drying temperature means a lower level of organic emissions as well as the possibility to exploit lower-level heat sources, such as the secondary process heat of pulp and paper mills.

4. A lower air flow permits the utilization of the exhaust air from the MSDS as part of the combustion air in the associated CHP plant boiler, even when drying the biofuel to a high extent.

5. When the fuel input to a CHP plant boiler is kept constant on a dry-matter basis, drying of moist biofuel in a MSDS leads to a measurable increase in electricity output.

6. Application of the MSDS should also permit an increase in dry-matter input, with consequent increases in power and heat production.

7. For CHP plants in pulp and paper mills, at least part of the heat for drying can be supplied by secondary process heat from the mill, further increasing the outputs of electricity and heat.

It should be noted that the performance evaluations may be somewhat optimistic because of: 1. uncertainty in the estimates of internal power consumption and 2. the fact that the (small) heat losses from the drying equipment have not been taken into account. However, these inaccuracies 1-2 are not expected to have significant effect on the above conclusions.

   With regard to organic emissions, it is concluded that significant condensation of organic compounds on surfaces of the MSDS equipment is not to be expected. For drying stages operating at relatively low temperatures, e.g. below approximately 100 $^{\circ}$C, direct discharge of the exhaust air into the atmosphere should be possible from the point of view of organic emissions. This measure would further improve the performance of the integrated CHP plant and MSDS. On the basis of the results of the study of drying kinetics, it is concluded that drying times should be acceptably short for the MSDSs under consideration.

   When assessing the competitiveness of biofuel drying, the benefits for the combustion process itself should not be overlooked. These benefits, which are particularly significant in smaller plants, include a more stable combustion process and reduced levels of flue-gas components that are not fully oxidized. The overall conclusion of this thesis is that the MSDS concept, developed and patented during the

course of this work, represents a promising method of improving the efficiency of energy production from biofuels in CHP plants. It is likely that this MSDS technology will prove advantageous in other fields as well.

Increasing the efficiency of energy production from biomass decreases the need for fossil fuels and so reduces net CO_2 emissions into the atmosphere.

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(I.)   Spets, J.-P. 2001: A New Multistage Drying System. In: Proceedings of 1st
         Nordic Drying Conference 27th-29th June Trondheim, Norway, Paper No. 13.
         ISBN 82-94-2073-2. 8 pp.

(II.)   Spets, J.-P. & Ahtila, P. 2001: Preliminary Economical Examinations for a New Multistage Biofuel Drying System Integrated in Industrial CHP-power Plant. In: Proceedings of 1st Nordic Drying Conference 27th-29th June Trondheim, Norway, Paper No. 14. ISBN 82-94-2073-2. 10 pp.

(III.)   Spets, J.-P. & Ahtila, P. 2001: A New Multistage Biofuel Drying System Integrated into an Industrial CHP-power Plant: Description of Process and Performance Calculations. In: Proceedings of 2001 ACEEE Summer Study on Energy Efficiency in Industry Vol. 2, July 24th-27th New York, USA, Pp. 67-78.

(IV.)   Spets, J.-P. & Ahtila P. Improving the power-to-heat ratio in CHP plants by means of a biofuel multistage drying system. Appl. Therm. Eng. 22(2002)10, Pp. 1175-1180.

(V.)   Spets, J.-P. & Ahtila P. Reduction of organic emissions by using a multistage drying system for wood-based biomasses. Accepted for publication in Drying Technology - An International Journal. Marcel Dekker, Inc.. 20 pp.

ATTACHMENTS

ATTACHMENT A: Ultimate analysis of wood and peat in calculations
(Chosen average compositions)

ATTACHMENT B: Additions and corrections to Papers I-V

ATTACHMENT A

ULTIMATE ANALYSIS OF WOOD AND PEAT
(Chosen Average compositions)

Element	Wood (Alakangas et al. 1987) [wt-% in DS without ash]	Peat (Lampinen 1996 HUT 90) [wt-% in DS with ash]
C	51	55
H	6.2	5.5
S	-	0.2
O	42.8	32.6
N	-	1.7
Ash	-	5

	[wt-% in DS]
Ash	0.5

MOISTURE CONTENT UNITS FOR MOIST FUELS:

$[wt\text{-}\%_{H2Otot}] \cong$ weight percent of water from total moist mass $\qquad$ (A1)

Moisture content of unit $[wt\text{-}\%_{H2Otot}]$ is changed to moisture ratio of unit $[kg_{H2O}/kg_{\text{dry solids}}]$:

$$[kg_{H2O}/kg_{\text{dry solids}}] \cong \frac{([wt\text{-}\%_{H2Otot}])}{(100 - [wt\text{-}\%_{H2Otot}])} \qquad (A2)$$