A NEW MULTISTAGE DRYING SYSTEM

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ABSTRACT

Most of the energy consumption in industry takes place in different drying operations. This article describes a new multistage drying system (MSDS), in which the drying air and wet matter to be dried is led through a series of direct-contact drying stages. The multistage drying system enables remarkable savings in the energy costs of drying. It also offers the possibility to use secondary energy from (i. e.) a plant facility as the drying energy.

The MSDS is suitable for drying materials, which can not stand high drying temperatures. The absorption capacity of the drying air is maintained by heating up the moist drying air in between each stage. The multistage structure makes it possible to use lower inlet temperatures or lower mass flows of drying air than in a single dryer system. The specific energy consumption of the multistage system is also smaller compared to conventional single dryer systems. In this paper calculations are applied to wood drying. In the specified case of a 4-stage drying system, the MSDS specific primary energy consumption (kJ/kg$_{H2O}$) is over 10 % lower compared to a single stage drying system with the same inlet temperature of drying air.

At the same time, the MSDS decreases the mass flow of fresh air into drying to 72%. Considering the previous, a single drying stage with an inlet air temperature of 106°C could be replaced with a MSDS with the inlet air temperature of about 50 to 60°C in each stage.

INTRODUCTION

The principles of single stage drying and multistage drying systems are shown in Mollier (i,x)-diagram in figures 1 and 2. Compared to the single stage case, the multistage drying system can operate with same or different inlet air feed temperatures into every single dryers. These are regarded as separate alternatives of multistage system's running functions. In multistage drying system the outlet stream of drying air is led through temperature rising and particles from previous drying stage into following one.

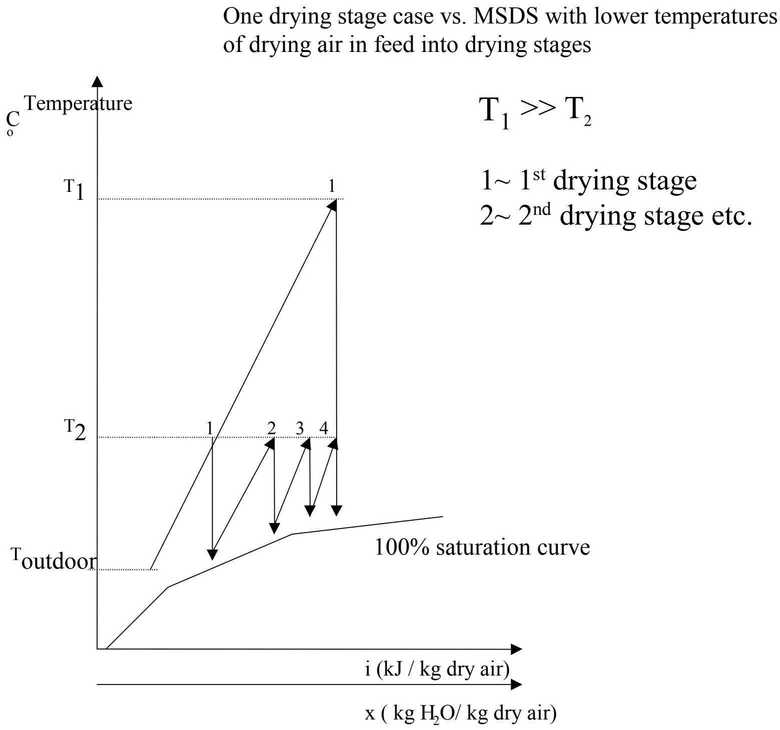

Figure 1. Comparison of one stage and multistage drying systems with different inlet air temperatures in Mollier (i,x)-diagram.

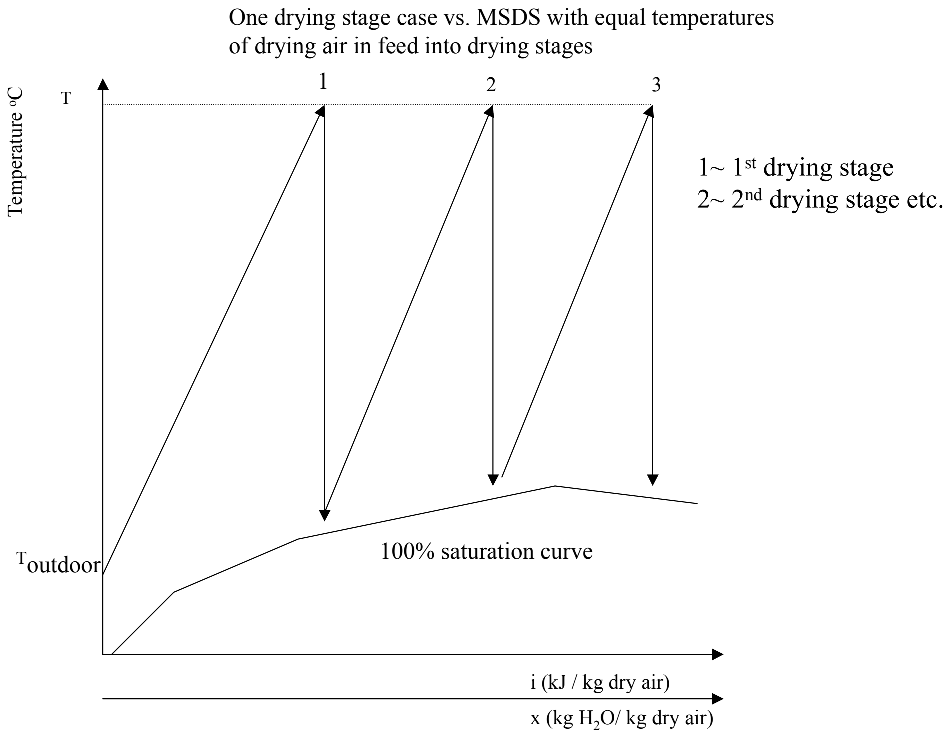

Figure 2. Comparison of one stage and multistage drying systems with same inlet air temperatures in Mollier (i,x)-diagram.

The energy consumption is caused by heating of drying air before the drying stage. The specific energy consumption Φ_{SEC} of drying for one drying stage is determined:

$$\Phi_{\mathrm{SEC}} = (\Delta \mathrm{i}\ \dot{\mathrm{m}}'_{\mathrm{da}} + \Phi_{\mathrm{ex}}) \,/\, (\Delta \mathrm{x}\, \dot{\mathrm{m}}'_{\mathrm{da}}) \qquad (1)$$

where $\Delta \mathrm{i}$ is entalphy change of drying gas in heating, $\Delta \mathrm{x}$ is change of moisture contentet of drying gas in drying stage, $\dot{\mathrm{m}}'_{\mathrm{da}}$ is mass flow of drying air and Φ_{ex} is a power to melt ice (in wintertime) and heat all initial wet fuel into the adiabatic saturation temperature of hot drying air entering the drying stage.

For 2nd-nth drying stages:

$$\Phi_{ex,(2-n)} = \dot{m}'_s\, c_{p,ds}(t_{s,n} - t_{s,n-1}) + \dot{m}'_w\, c_{p,w}(t_{s,n} - t_{s,n-1}) \qquad (2)$$

For 1st drying stage (ice melting in winter at 0 °C, $t_{\mathrm{out}} < 0$ °C):

$$\Phi_{ex,1} = \dot{m}'_s\, c_{p,ds}(t_s - t_{out}) + \dot{m}'_w\, c_{p,w}(t_s) + \dot{\mathrm{m}}'_{\mathrm{w}}\, \lambda_{\mathrm{m}} - \dot{\mathrm{m}}'_{\mathrm{w}}\, \mathrm{c}_{\mathrm{p,i}}\, (\mathrm{t}_{\mathrm{out}}) \qquad (3)$$

For 1st drying stage (without ice melting, tout ≥ 0 °C):

$$\Phi_{ex,1} = \dot{m}'_s\, c_{p,ds}(t_s - t_{out}) + \dot{m}'_w\, c_{p,w}(t_s - t_{out}) \qquad (4)$$

In equation (3) it is asssumed that all moisture of wood is frozen and has to be melted. λ_m is heat of ice melting. In multistage drying system the Φ_{SEC} is the sum of every terms for single drying stages ($z \geq 1$) :

$$\Phi_{\mathrm{SEC}} = \sum_{n=1}^{z} (\Delta i\, \dot{m}'_{da} + \Phi_{ex})_n \,/\, \sum_{n=1}^{z} (\Delta x\, \dot{m}'_{da})_n \qquad (5)$$

Thermal efficiency η of drying system is calculated as ratio between power needed for evaporating water in dryers and total power inputs into the drying stages:

$$\eta = \Big(\sum_{n=1}^{z} (\Delta \dot{m}'_w\, r(t_{s,n}))\Big)_n \Big/ \Big(\sum_{n=1}^{z} (\dot{m}'_{da}\, \Delta i + \Phi_{ex})_n\Big) \qquad (6)$$

CALCULATION

The drying of wood particle is regarded as:

1. Wet particle is heated into adiabatic saturation temperature of hot air (t_s).
2. Water is evaporating in that adiabatic saturation temperature.

While drying action in single drying stage the surface temperature of every single particles is kept in t_s, when the moisture content of wood particle is maintained over fiber saturation point (FSP). In calculation procedure is assumed, that the surface temperature is constant everywhere in drying stage space. That's not correct, because the heating of dry wood and moisture content and heat losses through drying stages' shells into environment cause cooling of drying air, which causes sinking of adiabatic saturation temperature of drying air inside drying stage space. To keep adiabatic saturation temperature constant in every single drying stages, extra heat Φ_{ex} flows is led into drying stage to compensate before named heat losses. This extra heat flow Φ_{ex} is noticed while calculating energy consumption figure of adiabatic drying process. In table 1 is shown process parameters and initial data for calculations.

Table 1. Process parameters and initial data.

Properties of wood	
Wood mass flow:	5.525 kg /s (ds)
u_{in}:	1.35 kgH_2O/kg ds (57.5 w-%$H_20_{total\ mass}$)
u_{out}:	0.28 kgH_2O/kg ds (22 w-%$H_2O_{total\ mass}$)
Dry wood solids heat capasity:	$c_{p,ds}$= (u+0.324) 4184 / (1+u) [kJ / kg K]
Ice heat capasity (according to Kopp's rule):	$c_{p,i}$= 2 kJ/ kg K
Outdoor temperature:	10 °C (Unless not mentioned)
Drying air into drying system	
Outdoor temperature:	10 °C (Unless not mentioned)
Relative humidity:	60 vol-%
Number of drying stages x (air temperature in):	1 ... 4 x (106 °C) and 4 x (50 °C)
$(t_{g,out}-t_s)_n$ in drying stages (unless not mentioned):	4 °C (outlet air and surface temperature difference)
All units and equations follow SI-standard.	

In tables 2 …5 are shown energy consumption values and dry air mass flows into drying operation for different drying system arrangements. Heat losses through drying stages' shells into environment are not included in calculations.

Table 2. Energy consumption values (different drying air temperatures in inlets).

No of stages [Pcs]	$t_{g,in}$ [°C]	Φ_{SEC} [kJ/kg H_2O] *)	η [%] *)
1	106	3770	64.3
4	50	3719	65.5

Table 3. Data for drying air flows (different drying air temperatures in inlets).

No of stages (Pcs)	$t_{g,in}$ [°C]	Mass flow [kg dry air/s]	x_{in} [kgH_2O/kg dry air]	x_{out} [kgH_2O/kg dry air]
1	106	214	0.005	0.032
4	50	206	0.005	0.033

Compared to single drying stage system, the multistage drying system has the following advantage: The inlet temperatures of equal dry air massflow can be lower into each drying stage.

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*) Without heat losses into atmosphere and power demand of process equipment.

Table 4. Energy consumption values (equal drying air temperatures in inlets).

No of stages (Pcs)	$t_{g,in}$ [°C]	Φ_{SEC} [kJ /kg H_2O] *)	η [%] *)
1	106	3770	64.3
4	106	3384	70.9

Table 5. Data for drying air flows (equal drying air temperatures in inlets).

No of stages (Pcs)	$t_{g,in}$ [°C]	Mass flow (kg dry air /s)	x_{in} (kgH2O/kg dry air)	x_{out} (kgH2O/ kg dry air)
1	106	214	0.005	0.032
4	106	60	0.005	0.103

When inlet temperatures of drying air into every drying stages in MSDS are the same than in single drying stage case, MSDS arrengement decreases the need of air massflow in feed into the system. That results from regenerative heating of drying air mass flow between every drying stages. The adiabatic saturation temperature is growing from the first drying stage to the last drying stage, because the water content of drying air grows. In tables 4 and 5 MSDS decreases the Φ_{SEC} of specified drying operation abt. 10.2 % and the mass flow of dry air into the drying abt. 72 %. In figure 3 is shown Φ_{SEC} of different drying sequences vs. $(tg,out-ts)_n$ in MSDS-system, when the final moisture content of wood is at least corresponding FSP=f($t_{s,n}$).

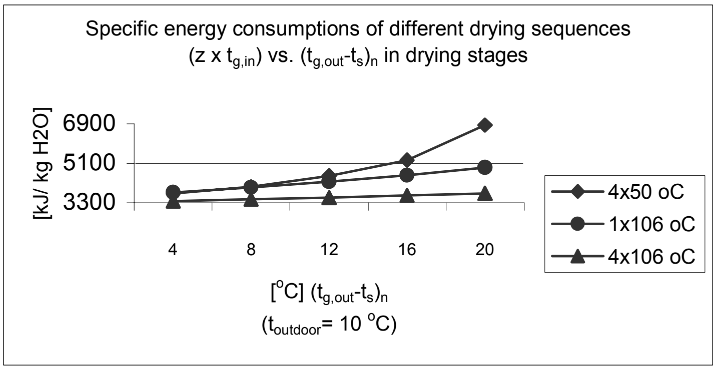

Figure 3. Specific energy consumption of different drying sequences as function of $(tg,out-ts)_n$ in drying stages, whenX_{out} > FSP (kg H_2O/kg solid).*)

In figure 3 is shown, that specific energy consumption differences $\Delta\Phi_{SEC}(4x50,1x106)$ and $\Delta\Phi_{SEC}(1x60,4x60)$ are increasing with increasing of $(tg,out-ts)_n$ in drying stages. In the same time, the drying time is decreasing vs. increasing of the $(t_{g,out}-t_s)_n$ in dryers. In figure 4 is shown Φ_{SEC} of drying operation vs. outdoor temperature and diffent drying sequences. In fig. 4 it is shown, that specific energy consumption Φ_{SEC} of 4x106-system decreases compared to specific energy consumption Φ_{SEC} of 1x106-system from 10.2 % at 10 °C to 18.1 % at –10 °C.

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*) Without heat losses into atmosphere and power demand of process equipment.

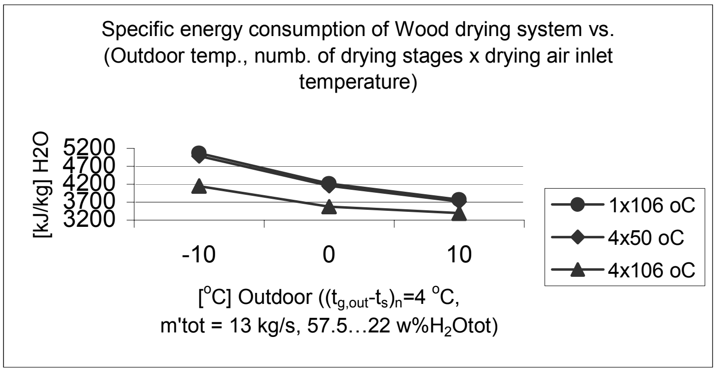

Figure 4. Specific energy consumption of drying operation as function of outdoor temperature and different drying sequences. *)

In figure 5 is shown the specific energy consumptions Φ_{SEC} and thermal efficiencies τ of drying operation vs. the number of drying stages with constant process parameters and outdoor temperature.

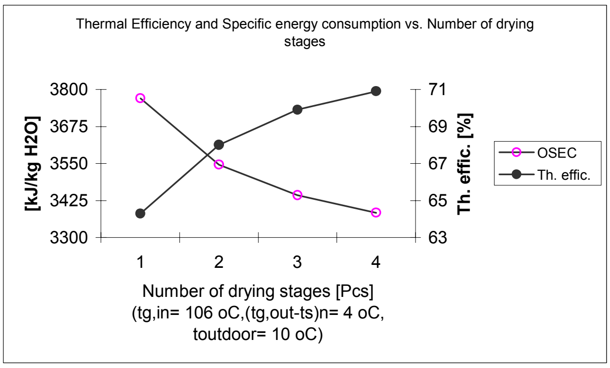

Figure 5. The specific energy consumptions and thermal efficiencies of drying operation as function of the number of drying stages at constant outdoor temperature. *)

It can be read from the figure 5, that the more the drying stages are used the less is the specifig energy consumption of drying operation. In the same same the thermal efficiency of MSDS increases with increasing number of drying stages. The reasons for improvement of energy efficiency of drying operation are the decreasing of mass flow of drying air vs. increasing number of drying stages and the decreasing of heat of water evaporation vs. increasing of surface temperature $t_{s,n}$. In reality the availability of process, the internal power consumption of process equipment and the thermal stability of dried material are the main parameters for specifying the sensible number of dryers in MSDS.

DISCUSSION

Only feed gas flow into drying system was iterated in order to reach given moisture change of wood in drying system. The adiabatic saturation temperatures was calculated with another Excel-file calculation (application of Clausius-Clapeyron' equation) and set in process calculation file as process values. That may cause relative error in calculated results. Process calculations need another iterative steps for

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calculating saturated adiabatic temperatures in the following dryers as a function of state of exit drying air from the previous drying stage.

CONCLUSION

Multistage drying system (MSDS) makes it possible to use lower temperature inlet air flows into dryers than in one dryer case. Multistage drying system makes it also possible to decrease mass flow of drying air into the drying system compared to one dryer case, when inlet temperatures of drying air are the same than in one dryer case.

The first advantage makes it possible to utilize low temperature secondary energy flows in drying. This improves the energy efficiency of power plant etc. The second advantage makes it possible to arrange that kind power boiler - MSDS -integrate, where it is possible to lead almost all exit drying air flow into the combustion process as burning air flow. This makes it possible to destroy organic compounds from dried organic matter in combustion stages in power boiler.

Depending on the structure of the MSDS, even 100 % of the drying air can be utilised as combustion air. The MSDS also enables an increase of the power boiler 's solid burning capacity , which in example case*) at +10 % level would produce about 2.4 % more of net heat and 16.4 % more of net power at the generator terminals subtracted by the power demand of the boiler - MSDS process than boiler without MSDS. In addition, the improvement in CHP can be reached with decreased emissions of unburned organic compounds and CO from combustion as a result of the improved quality of the biofuels. When compared to direct steam drying, the MSDS also minimises or even eliminates the formation of condensates from the drying operation.

The internal power consumption of main process equipment of boiler-MSDS -integrate is abt. 2.2 % of steam effect of FBB, which corresponds the electric power consumption of abt. 22 kW_e/ MW steam effect of FBB. The exact values depend on process values, number of drying stages and lay out of power boiler-MSDS -integrate.

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*) Specified wood residues and peat firing fluidised bed power boiler of Stora Enso Oyj Mill in Finland. Calculations have been done for wood drying in MSDS from 57.5 w-%H_2Otot to 22 w-%H_2Otot. MSDS utilises secondary energy flows, back-pressure and exctraction steams from steam turbine for drying.

NOTATION

i	Enthalpy of dry gas	kJ/kg dry gas
$\dot{m}'$	Mass flow	kg/s
c_p	Heat capasity	kJ/kg ^oC
Φ	Heat flow	kJ/s
$r(t_s)$	Heat of vaporization of water at temperature ts	kJ/kgH_2O
t	Temperature	^oC
u / x	Moisture content of wood / air	kg H_2O/ kg dry solids kg H_2O/kg dry air

Greek Symbols

Δ	Change	(Inlet-outlet)
λ	Heat of phase change	kJ/kg
η	Thermal efficiency of drying	%

Substripts

da / ds	dry air / dry solids	n	n^{th} drying stage
e	extra	out	outlet or outside air
g	gas	s	saturation (100%)
i	ice	SEC	specifig energy consumption
in	inlet	w	water
m	melting	z	number of dryers

LITERATURE

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