15th International Drying Symposium (IDS 2006)
Budapest, Hungary, 20-23 August 2006

SIMULATION BASED ANALYSIS OF THE INFLUENCE OF IMPINGEMENT DRYING ON THE ENERGY CONCEPT OF A PAPER MILL INTEGRATE

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Abstract: The need to increase paper production capacity and simultaneously the quality of the paper is achieved among others by intensifying the performance of the paper machine drying section. To test new and improve existing drying concepts good simulation tools and experimental measurements are needed. Dryer simulator built on basis of a commercial mass- and energy balance simulator BALAS® is described. It is capable of simulating traditional cylinder, new combined cylinder/through fabric and direct impingement drying configurations accurately. A paper mill integrate was simulated to make energy concept considerations of impingement drying rebuilds and new installations.

Keywords: impingement, drying of paper, BALAS®, simulation, energy

INTRODUCTION

The need to increase paper production capacity has led to new paper drying concepts, from conventional to single-tier configuration and to combined cylinder impingement drying. When considering the re-building of the existing paper machine or the building of a new one the drying section plays a crucial role. It takes nearly 3/4 of the energy (steam) needed in the whole paper mill integrate and therefore it mainly defines the structure of the integrate energy concept.

In recent years many laboratory scale measurements of heat transfer coefficient, drying rate of paper and web/cylinder temperature of paper drying concepts have been made (Timofeev et al., 2002; Milosavljevic and Heikkilä, 2004; Talja et al., 2000; Poirier et al., 2004). Measured values are then used in simulations to predict the behaviour of these concepts in real paper machines (Talja et al., 2000; Sadeghi and Pikulik, 2004; Lindell and Stenström, 2004) and in completing the formulation of the drying phenomena to function in commonly used temperatures and machine speeds (Milosavljevic and Heikkilä, 2004).

To understand fully the influence of the drying section modifications on the paper mill integrate simulations of the energy concepts of the whole integrate are needed. Even though the heat and mass transfer are known, only estimates of this influence are made and they are mainly based on separate calculations, (Talja et al., 2000; Lindell and Stenström, 2004). To be able to calculate the influences correctly the behaviour of all heat and mass transferring substances need to be described in detail throughout the entire integrate. This means not only the web but also steam, fabric and hood air.

This paper describes modelling and simulation of the drying section and paper mill integrate with BALAS® simulation software and gives examples of integrate energy concept considerations.

MODELING OF DRYING

The software used in simulations was BALAS®. More information of the simulator can be found from http://balas.vtt.fi.

New unit operation modules were created to model the drying section of a paper machine in detail. The modeling of drying is mainly based on PaperNova drying simulator (Karlsson and Timofeev, 1994; Timofeev et al., 1995), which is also developed at VTT. Also other sources for drying of paper, heat transfer and mathematical modeling techniques were used (Heikkilä, 1993; Heikkilä and Milosavljevic, 2001; Heikkilä and Milosavljevic, 2002; Heikkilä and Milosavljevic, 2003; Incropera and De Witt, 1990; Martin, 1977; Timofeev, 1987).

The possible drying section configurations in use today can consist of conventional double or single tier, combined cylinder and through fabric impingement or combined vacuum roll and direct impingement drying. Unit operation modules with convertible amount of cylinder-cylinder or cylinder-vacuum roll pairs were made to model all possible kinds of cylinder groups, from one pair to whole drying section.

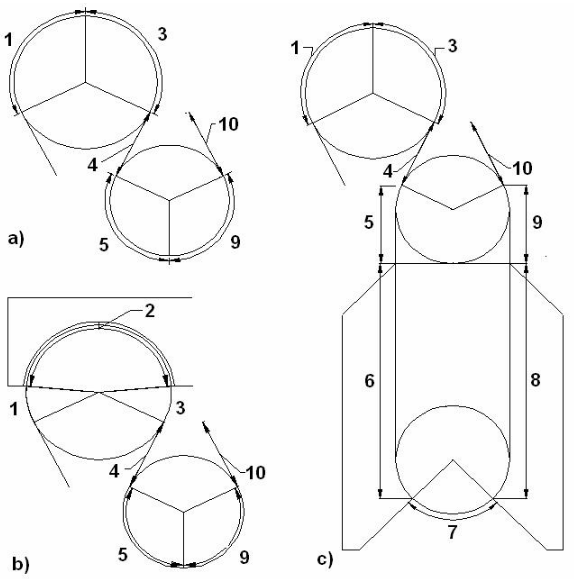

Fig 1. Configurations: a) single tier, b) combined cylinder and through fabric impingement and c) combined vacuum roll and direct impingement.

Cylinder geometry and the state of hood air in different places in the hood divide the drying phenomena in machine direction into zones. There are five different types of drying zones, cylinder, combined cylinder and through fabric impingement, free draw, vacuum roll and combined vacuum roll and direct impingement zones. For example the sequence cylinder - free draw - vacuum roll - free draw constitutes a conventional cylinder vacuum roll pair in single tier configuration (Fig. 1.a). Every zone is yet divided into short intervals to integrate numerically the transferred heat and mass and hence the temperature and moisture development of web accurately.

In cross machine direction the drying is assumed to be even and therefore one dimensional model of web is sufficient.

To find out the temperature at the end of each interval the heat transfer between cylinder-, fabric-, air and web is needed. Heat transfer between two substances *i* and *j* can be expressed as

$$\dot{Q}_{ij} = A\alpha_{ij}\left(T_i - T_j\right) \qquad (1)$$

where *A* is the heat transfer area, *α* heat transfer coefficient and *T* temperature. Correspondingly for the moisture content of web the water transferred between the web and hood air is needed. Mass transfer between the web and air *i* is

$$\dot{m}^{i}_{H_2O} = A\beta^i\left(\Gamma\, p^{web}_{H_2O} - p^{air}_{H_2O}\right) \qquad (2)$$

where *β* is mass transfer coefficient, Γ adsorption isotherm of web and p_{H2O} vapor pressure. The heat and mass transfer coefficients in the different zones are diverse. The contact heat transfer coefficient between the cylinder and web is

$$\alpha_{contact} = a + bZ + cZ^2\,. \qquad (3)$$

Here constants *a*, *b* and *c* are parameters and *Z* moisture content of web. The temperature of vacuum rolls in single tier configuration is assumed to reach the temperature of the fabric and therefore no heat is transferred between vacuum roll and fabric.

The heat transfer coefficient between web and air *i* is

$$\alpha_{a_i p} = K_H \frac{\lambda_i}{l} Re_i^{0.78} Gu_i^{0.175} \qquad (4)$$

where *K* is a parameter, *λ* thermal conductivity of air, *l* heat transfer distance, *Re* Reynolds number and *Gu* Gukhman number. Heat transfer coefficient between web and air *i* through fabric is

$$\alpha_{a_i p\_f} = \frac{1}{\dfrac{1}{J_0 \alpha_{a_i p}} + \dfrac{\delta_f^b}{\lambda_i \varepsilon_f}} \qquad (5)$$

where *J* is turbulence factor of fabric, *δ* boundary layer thickness of fabric and ε porosity of fabric. Similarly the mass transfer coefficient between web and air *i* is

$$\beta_i^0 = K_M \frac{D}{l} Re_i^{0.78} Gu_i^{0.1} \qquad (6)$$

where *D* is mass diffusivity and *l* mass transfer distance. Coefficient through fabric is

$$\beta_i^{00} = \frac{1}{\dfrac{1}{J_f \beta_i^0} + \dfrac{\delta_f^b}{\varepsilon_f D}} \frac{1}{R_{H_2O} T_p}. \qquad (7)$$

Here R_{H2O} is the gas constant of vapor. The heat and mass transfer coefficients between impingement air and web are

$$\alpha_{a_i p} = I_H \frac{\lambda_i}{l} Re_i^{2/3} Pr_i^{0.42} F \qquad (8)$$

and

$$\beta_i^0 = I_M \frac{DM_C Re^{2/3}}{lR_{H_2O} T_p \sqrt{\varepsilon}} \left(\frac{3600 v_i}{D} \right)^{0.42} \qquad (9)$$

where *Pr* is Prandtl number and the constant F is

$$F = \frac{M_C}{\sqrt{\varepsilon}} C_{Imp} \left(a + b\left(1 - Z_p\right)\right). \qquad (10)$$

Here ε is contraction correction factor, C_{Imp} air impingement multiplier, *a* and *b* constants and M_C Martin correlation

$$M_C = f\left(\varepsilon, H, D, f_A\right). \qquad (11)$$

These correlations are based on measurements of heat and mass transfer between relatively low temperature impingement air and smooth surface (Martin, 1977) and thus need to be modified to handle temperatures used normally in these drying applications. Therefore the correlations are weighted with temperature dependent coefficients I_H and I_M whose values are taken from literature (Milosavljevic and Heikkilä, 2004).

The fabric reduces the heat and mass transfer further and is handled with another weighting coefficient. Heat and mass transfer coefficients through fabric are therefore

$$\alpha_{ap\_f} = 0.5 \alpha_{ap} \qquad (12)$$

and

$$\beta_i^{00} = 0.5 \beta_i^0 \qquad (13)$$

where the coefficient *0.5* is from drying rate measurements at impingement air temperature around 200 °C and with very open impingement drying fabrics (Talja et al. 2000).

Due the high impingement air temperatures heat is also transferred by radiation from impingement nozzle. Heat transfer coefficient for radiation heat transfer between two surfaces can be stated as

$$\alpha_{rad} = \frac{\sigma}{\frac{1}{\varepsilon_n} + \frac{1}{\varepsilon_s} - 1} \frac{T_n^4 - T_s^4}{T_n - T_s} \qquad (14)$$

where ε is emissivity. Heat transfer coefficient between air and fabric is assumed to be the same as between free web surface and air.

With all coefficients known the heat and mass transfer in the interval (Equation 1 and 2) and therefore the temperature of the web after the interval can be calculated with Eulerian integration method

$$T_p^i = T_p^{i-1} + \frac{A \sum_i \dot{Q}_i}{C_{p,p} \dot{m}_{bdp} + C_{p,H_2O} \dot{m}_{H_2O}} \qquad (15)$$

where C_p is heat capacity and *m* mass flow. The sum goes through all the heat fluxes to and from the web. The moisture content of web is correspondingly

$$Z_p = Z_p^{i-1} - \left(\dot{m}_o^i + \dot{m}_f^j \right). \qquad (16)$$

The states of hood air differ from place to place in moisture content and temperature. For example the air in the cylinder and vacuum roll pocket is typically moister than air in cellar and hood and therefore pockets need extra ventilation. In the model air states are handled by introducing five different airs to web in a cylinder group: cylinder air (hood air above cylinder zone), cylinder pocket air, cellar air, vacuum roll pocket air and impingement air. Heat and mass transfer is thought to happen between the web and the nearest air of the corresponding zone at both sides, e.g. in free draw zone transfer is between the web and cylinder pocket air at the free side and between the web and vacuum roll pocket air at the felted side of the web. Because of continuous mixing of airs such sharp boundaries do not exist in reality but this way of modeling the air states is sufficient.

There is also a temperature and moisture gradient in machine direction inside the hood. Because of the partition of the drying section to cylinder groups the gradients through the machine are not continuous as in real machines, but stepped. The hood air is circulated to maintain the drying condition, in the model maintaining the condition means transferring the heat and water in every calculation interval of same zone to air of same temperature and moisture content. This leads to iterative solving of air moisture content and temperature inside the cylinder group because the total transferred heat and water inside the group to every air is unknown.

The heat flux from cylinder surface to the web is calculated also only by iteration. Surface temperature of every cylinder is assumed to be constant due its fast rotation speed. On the other hand the inner surface temperature is commonly known to settle to the condensation temperature of steam. From the heat transfer equation through the cylinder shell the surface temperature of cylinder can be solved to be

$$T_{cyl}^{out} = T_{cond} - \frac{\dot{Q}_{shell} \delta_{shell}}{\lambda A}. \qquad (17)$$

Here δ is shell thickness and λ thermal conductivity of cylinder shell. Heat flux $\dot{Q}_{shell}$ is the sum of heat from cylinder to web and heat losses from cylinder heads and free surface in the cylinder pocket to the pocket air. Both of the heat fluxes are results of air iterations: heat from cylinder to web is a function of web moisture content and heat losses a function of air temperature. In addition, the heat flux itself affects on air properties.

Quasi-Newton solver is used to solve the nested iterations of temperatures and moisture contents of airs and cylinder surface temperatures in every group alone.

All needed physical properties of airs, web and fabric are calculated with the own routines of BALAS®.

SIMULATION MODELS

Base case

The drying section of a typical fine paper machine connected to a CHP power plant was simulated. No specific mill was considered but well known values for production, cylinder geometry of drying section and steam pressures were used to get as realistic simulation model of drying as possible. The basic data of the mill is listed in Table 1.

Table 1. Mill data.

Speed	1200 m/min
Width	9.4 m
Grammage	80 g/m^2
Production	1300 t/d
Amount of glue to sizing	3 g/m^2

Dryer section consist of pre dryer section with five cylinder groups, sizing unit, air dryer and after dryer section with three cylinder groups. Last group is a double tier, all others single tier groups. Cylinder groups are connected to a cascade steam system with 10 % discharging steam. Condensates are circulated back to power plant. Number of cylinders in cylinder groups and steam pressures in them are in Table 2.

Table 2. Cylinder group steam pressures.

	Cylinders	P_{steam} (kPa a.)
Pre section	5/8/8/10/3	40/150/210/225/260
After section	3/3/6	100/150/140

Air dryer specifications are listed in Table 3.

Table 3. Air dryer data.

Length	3.75 m
Impingement velocity	50 m/s
Impingement temperature	325 °C
Burner fuel load	7.3 MW (HHV)
Drying rate	102 kg/m^{2}h

Air moisture content in pre and after dryer section hoods was 160 g/kg dry air and in air dryer 150 g/kg dry air, corresponding temperatures 82 °C and 150 °C. Leakage air amount into hoods was set to 35 % of the amount of hood exhaust air.

Web dry content profile can be seen in Fig. 2.

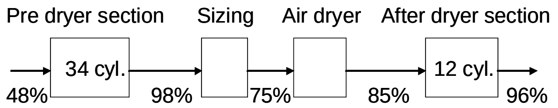

Fig 2. Web dry content profile

Impingement drying cases

Two comparison cases with impingement drying added to the conventional drying configuration were made. A rebuild of the base case dryer section and a new installation paper machine with a similar power plant as in base case were studied.

In rebuild case the paper machine was held the same as in base case, only impingement drying was added to the first cylinder group. Under the third vacuum roll total 11.6 m impingement drying was added (Fig. 1.c). The impingement air was heated with gas and blown towards the web which is against the fabric in vacuum roll zone. The extra drying efficiency gained with impingement drying together with the drying efficiency of the base drying section cause over drying without speeding up the machine. The speed was therefore raised to achieve 98 % web dry content after pre dryer section. On the other hand the speed increase induces need of extra drying efficiency also in air dryer and after dryer section. They were attained by lengthening the air dryer and by adjusting the pressure levels of the three cylinder groups of after dryer section. The speed increase causes also some web dry content reduction in the pressing section which is assumed to be 1 % per 100 m/s speed increase. The modified mill and drying section data of rebuild case are listed in Table 5.

Table 5. Rebuild specifications.

Capacity increase	10.8 %
Dry content after press	46.7 %
Impingement temperature	375 °C
Impingement velocity	90 m/s
Impingement air moisture	250 g/kg dry air
Air dryer length	4.13 m
Air dryer fuel load	8.3 MW
After dryer steam pressures	120/160/170 kPa a.

In new installation case same kind of impingement drying unit was used as in rebuild case but the speed was held the same as in base case by removing total 5 cylinders from the three middle cylinder groups of the pre dryer section. This way the web dry content profile of the new installation and hence the production of the mill was precisely the same as in base case but the total physical length of the drying section would be about 10 m shorter.

Power plant

Power plant used in simulations was a CHP plant. The energy configuration of the mill integrate is sketched in Figure 3. and basic parameters of the modelled typical Finnish CHP power plant are listed in Table 4.

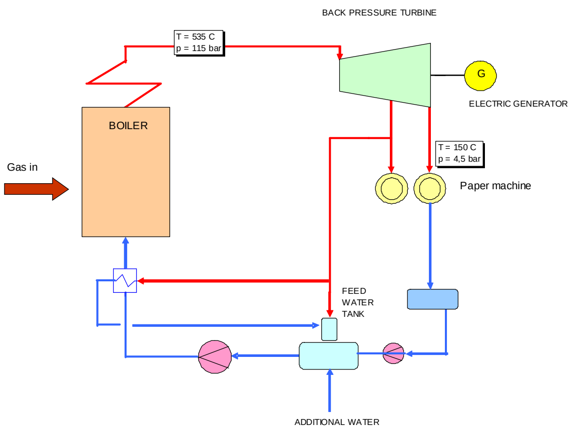

Fig 3. Energy concept of the mill.

Table 4. Power plant data.

Boiler fuel load	76.9 MW (HHV)
Turbine generator output	15.5 MW
Power prod. efficiency	20.2 % (HHV)
Power-to-heat ratio	0.272 (HHV)
Boiler efficiency	94.2 % (HHV)

The drying section is the main steam consumer in the mill integrate. The amount of steam needed in new installation case is lower than in base case because of smaller amount of cylinders and hence steam and electricity produced in power plant are lower. Power plant data of new installation is in Table 6.

Table 6. Power plant data of new installation case.

Burner fuel load	64.7 MW (HHV)
Turbine generator output	13.1 MW

RESULTS

To present and interpret the results, temperature profile of web and cylinder surfaces, web moisture content and average drying rate in machine direction were logged during the simulations. In addition to that flow, temperature, enthalpy and composition information of all substances needed to model the mill integrate were gathered from BALAS®. An example log is presented in Figure 4.

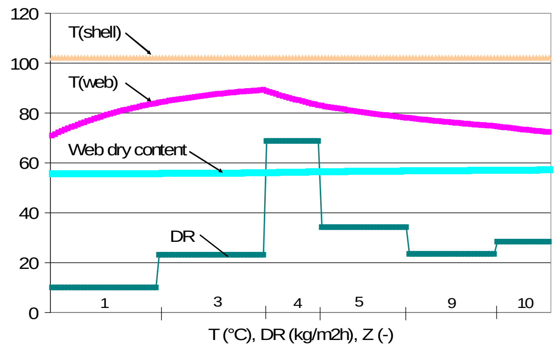

Fig 4. Example curve.

The three different zones of cylinder drying can be seen in drying rate curve. The cylinder and vacuum roll zones are split to two parts due the possible impingement zone in the middle of these zones (Fig. 1) and total of 6 zones can be seen: two cylinder zones (1 and 3), one free draw zone (4), two vacuum roll zones (5 and 9) and one free draw zones (10). Temperature of web increases during the cylinder zone and decreases during free draw and vacuum roll zones. Cylinder shell temperature is constant in one cylinder vacuum roll pair but can change between pairs and web dry content increase only slightly in one pair but notably more in longer part (Fig. 5).

Base case

The log of the third cylinder group is illustrated in Figure 5.

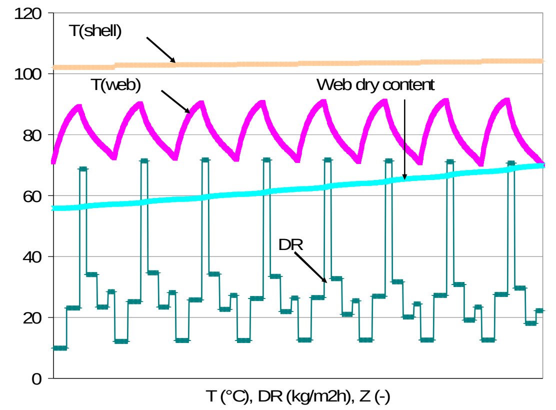

Fig 5. Web and cylinder temperatures, average drying rate and web moisture content of 3rd cylinder group.

Drying rate is highest in free draw zones after every cylinder zone because of high web temperature and free web surface evaporation to the cylinder pocket. After fast cooling of web in free draw zone, drying rate is decreased notably in vacuum roll zones. During the third cylinder group web dries almost 10 %.

Impingement cases

In rebuild case the third cylinder group looks the same as in validation case, therefore the first group with impingement drying is presented as being more interesting (Fig. 6).

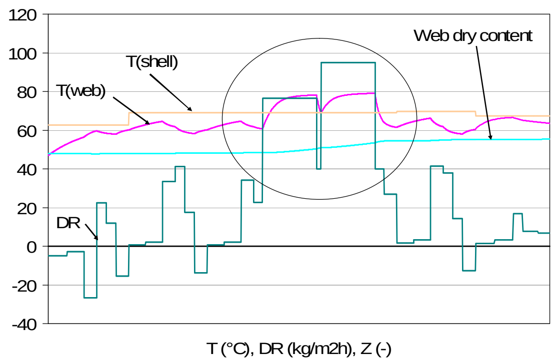

Fig 6. Web and cylinder temperatures, average drying rate and web moisture content of 1st cylinder group.

Low web temperature at the beginning of drying section induces lower vapor pressure on the web surface than the vapor pressure of hood air. Therefore mass transfer is from air to web and web becomes even wetter. After cylinder zones water is also evaporated due the higher web temperatures. Impingement drying however gives a tremendous rise to drying rate (circle in Fig. 6). Direct hot impingement brings a lot of energy to the web and the long impingement zone produce a leap in web dry content. The simulated drying rates of direct impingement drying correspond also well to published values ranging from 90 to 400 kg/m^{2}h (Talja et al. 2000, Poirier et al. 2004).

The drying in new installation case is the same as in base case and the influence of impingement drying follows the rebuild case.

Energy aspect

The steam, gas and electricity needed in drying sections of the studied cases are presented in Figure 7. The specific energy demands are also listed in Table 7.

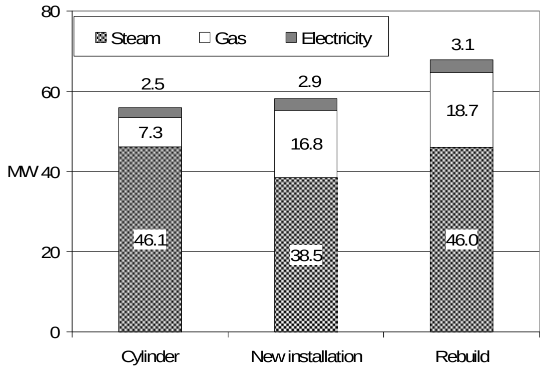

Fig 7. Needed energy in drying section

Table 7. Specific energy demand of drying.

Base case	3.64 GJ/t
New installation case	3.79 GJ/t
Rebuild case	4.03 GJ/t

Specific energy demand of base case is in good agreement with common knowledge. The value is measured to be between 3.5 and 4.0 GJ/t in today's fine paper mills.

The total energy demand of rebuild case is substantially higher than in base and new installation cases because of higher capacity of machine. The higher specific energy demand is due the lower input web dry content meaning more water to evaporate. Steam needed in cylinder drying is the same as in base case and increase in electricity demand comes from shaft power used in impingement drying units.

In new installation case the steam amount is lower due the shortened cylinder drying part. Total amount of energy used in new installation case is a bit higher than in base case even though production is the same because a large amount of energy is lost with moister and warmer impingement exhaust air and because more electricity is needed in impingement drying units.

The mill fuel demand and power plant electricity production of all studied cases are listed in Table 8.

Table 8. Mill fuel demand and electricity production.

Fuel demand (MW)	Base case	New installation	Rebuild
Power plant	76.9	64.7	76.9
Paper machine	7.3	16.8	18.7
Total	84.2	81.5	95.6
Electricity production (MW)	15.5	13.1	15.5

Because the power plant is the same in rebuild case as in base case, only the paper machine fuel demand is increased and therefore also total fuel demand of the mill is increased. In new installation case the total fuel demand is reduced. Reduction result from impingement drying, increased fuel demand of impingement drying units is smaller than decreased fuel demand of power plant and the sum is smaller than in base case. In addition to that the electricity production of CHP plant is diminished.

Perhaps the best way to compare the cases is to compare their energy and production costs. The investment costs are not considered.

The energy costs of integrate are calculated with two different power plant fuel prices (Table 9.). The gas is assumed to cost 20 €/MWh, electricity 30 €/MWh, the operating time of mill is thought to be 8000 h/year and all electricity produced to be sold to the national network.

Table 9. Energy costs.

Fuel price	20 €/MWh	10 €/MWh
Base case	22.10 €/t	8.16 €/t
New installation	22.42 €/t	10.69 €/t
Rebuild	23.86 €/t	11.17 €/t

If the price of fuel is the same as the price of gas the energy costs of impingement drying cases are not remarkably higher. With cheaper fuel, for example biofuel, the conventional drying is much cheaper due the bigger part of drying made with the cheap fuel rather than with expensive gas as in impingement cases. The rebuild case seems to be always the most expensive from energy point of view. Capacity increase however brings up the profits. For example with fine paper price 790 €/t the profit would be 34.5 M€/year. On the other hand in new installation case savings can be gained at investment time, the new 10 m shorter machine line with only 29 cylinders in pre dryer section is cheaper, as is also the smaller power plant.

CONCLUSIONS

A physical model of cylinder and impingement drying of paper was implemented in commercial steady state simulator BALAS® to evaluate the influences of impingement drying to mill energy concept.

The simulation model of mill integrate was created on basis of well known properties of different parts of integrate. Three drying section cases, conventional cylinder drying, a rebuild of it and a new installation impingement drying were simulated.

The simulated base case depicts well a typical paper mill. Because real machine parameters were not available actual validation was not possible, but all estimated values produced the well known drying rates and temperature profile. Also the drying efficiency of simulated impingement cases corresponds well to common knowledge. For precise validation thorough measurements of drying section airs, steam, condensates, web, fabrics and cylinders should be made.

With BALAS® the energy aspects are very easy to establish. Also the logging of drying phenomena enables the precise studying and validation of the drying model

The power plant fuel constitutes mainly the energy costs of drying, also in the impingement drying cases. Therefore it has an important role in decision making, for example between a rebuild and new installation. In rebuild case the capacity increase has even more significant influence to the mill total expenses as the fuel.

NOMENCLATURE

Roman letters

A	area	m^2
a, b, c	constants	
c_p	heat capacity	$kJkg^{-1}K^{-1}$
C_{imp}	air impingement multiplier	
D	mass diffusivity	m^2h^{-1}
Gu	Gukhman number	
I, K	parameters	
J	turbulence factor of fabric	
l, l_{char}	characteristic length	m
M_C	Martin correlation	
m	rate of mass transfer	kgs^{-1}
p_{H2O}	vapour pressure	kPa
Q	rate of heat transfer	W
R	gas constant	$m^3Pamol^{-1}K^{-1}$
Re	Reynolds number	
T	Temperature	°C
Z	moisture content	$kg_{H2O}kg^{-1}$

Greek letters

α	heat transfer coefficient	$Wm^{-2}K^{-1}$
β	mass transfer coefficient	$kgm^{-2}s^{-1}$
δ	thickness	mm
Γ	adsorption isotherm	
ε	contraction correction factor, emissivity	
λ	thermal conductivity	$Wm^{-1}K^{-1}$
ν	kinematic viscosity	m^2s^{-1}
σ	Stefan-Boltzmann constant	

Subscripts

a_ip, 0	from air i to paper
a_ip_f, 00	from air i to paper through fabric
cond	condensation
f	felted
i, j	indices
H	heat
M	mass
n	nozzle
o	open
p	paper
rad	radiation
s	surface

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Risto Talja from Metso Corporation for his valuable technical support during the project.

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