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Thermodynamic and Heat Transfer Evaluation of Pocket Drying Section in the Multi-Cylinder Dryers of Paper Machine

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ABSTRACT

In this study a developed model has been used to evaluate the paper drying process and examine the pocket dryer conditions of a multi-cylinder fluting paper machine. The model has been developed based on the mass and energy balance relationships in which the heat of sorption and its variations with paper temperature and humidity changes have been taken into account. The applied model can be used to compute the drying parameters and analyze the pocket drying conditions. Furthermore, the effects of web tension on the heat transfer have been investigated. In the available operating range of the web tension, the overall mean heat transfer coefficient will be within 300-550 $W/m^2.K$. The pocket air temperature was between 50 and 90^oC. The dew point temperature was not close to the pocket air temperature and dew drop never happened during the dryer section.

Based on the modeling result and using a novel technique, the maximum level for the exhaust air in the studied machine can be estimated to be 0.2 kg H_2O/kg dry air. Result shows that increasing the exhaust humidity to the optimal level will lead to 4% reduction in the required energy and 20% rise in the heat recovery potential. Accordingly the specific heat consumption per evaporated water for the studied drying section can be reduced from 3.96 to 3.81 GJ per ton water.

1. Introduction

The drying operation is principally a simultaneous heat and mass transfer process which plays a significant role in almost all industrial sectors [1]. The drying process is an essential section in the paper production which is designed to evaporate the water content in the wet paper up to a certain desired level.

Paper manufacturing is one of the world's most energy consuming industries. The drying process typically consumes 80% of the total steam and more than 65% of the total energy required in the paper mill [2-5].

The conventional drying process in the paper mill is multi-cylinder drying section.

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That is, it generally consists of a series of rotating steam heated cylinders on which the paper web continually passes and steam inside the cylinders provides the heat energy which is transferred to the dryer cylinder. This energy is absorbed by wet paper web and the evaporated water is released in the dryer pocket [6]. Dryer pocket is defined as the space in the dryer section between two adjacent cylinders, in case of single-tier system, or between three cylinders, in case of two-tier system. Individual pocket is separated by dryer fabric and paper web [7]. The ventilation air in the pocket dryers is an important parameter for the drying process which is used to carry away the water vapor from the drying surroundings to prevent dripping on the paper web and can enhance the energy efficiency [8]. The main purpose of the pocket ventilation system is to remove the evaporated water to prevent condensation.

Fig. 1 shows the schematic layout of pocket ventilation for two tier dryer in a multi-cylinder drying section of a paper machine.

It has been proved that mathematical modeling is a powerful tool to optimize the paper drying process. Frequently the main objectives in the paper dryer

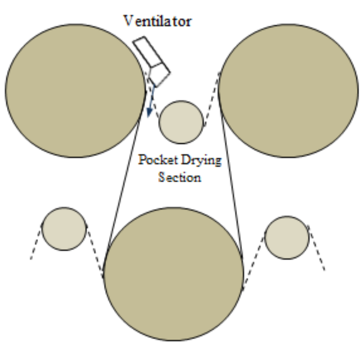

Figure 1. Pocket ventilation for two tier multi-cylinder dryer section.

modeling are the estimation of the profiles of web moisture and temperature in the machine direction. So, modeling the paper drying process has attracted the attention of many researchers.

One of the initial studies in the field of the paper drying has been carried out by Nissan and his co-workers. They have presented the theory of four phase divisions for multi-cylinder drying section. Their mathematical models were described in terms of a second order partial differential equation and proper boundary condition for each drying phase [9,10].

Several works from Wilhelmsson have focused on modeling the paper machine drying section. He developed a dynamic model for drying section of paper machine by using the heat transfer in the cylinder and paper that it does not include internal mass transfer of water in the thickness direction. The latent heat from steam is only considered as energy source to evaporate moisture from the paper web [11-14].

Karlsson and Stenstörm developed a dynamic model to describe the drying process of the cardboard. This model included shrinkage effect and could predict temperature, moisture and pressure profiles in the drying process. All derivatives for the mass balance equation and following the energy balance were approximated with a finite difference scheme [15-17]. Yeo *et al*. modeled the paper drying process for a multi-cylinder drying section based on the heat and mass balances. In their model, the heat transfer coefficients have been represented effectively in terms of web basis weight (grammage), moisture content and machine speed [18]. Berrada *et al*. have presented a state variable model for the paper machine drying section based on the mass and energy balance relationships written for paper, steam, moisture and cylinder dryer [19-21]. The simulation models can be utilized to evaluate the energy efficiency and heat recovery performance in the drying section of paper machines. Sivill *et al*. have developed a simulation program based on the thermodynamic modeling to improve the performance of heat recovery system of paper machine [22]. Laurijssen *et al*. presented several options to reduce the heat consumption in conventional multi-cylinder dryers and considered their influences on the energy usage [4]. Chen *et al*. have investigated a comprehensive method for assessing the energy performance of the paper dryer section to improve energy efficiency. Several significant energy saving measures were suggested to improve the energy efficiency in their model [23]. Ghodbanan *et al* have developed a steady state model for multi-cylinder fluting drying section by using the Nissan's theory and Berrada's physical model with the addition of the sorption heat and its variations in the heat conservation equation. The developed model is based on the mass and energy balance which can be properly employed to evaluate the drying and heat recovery performance in the drying section [24].

In this research based on the developed model, a novel technique was used to determine the allowable maximum range for pocket drying section and accordingly the thermodynamic conditions of the pocket drying section and heat recovery performance of the fluting paper machine were optimized. Also, based on the modeling results, the effect of fabric tension on the heat transfer coefficients was investigated.

2. Description of developed model

Two main equations of the model formulation were mass and energy balance equations to compute the moisture and temperature gradient.

The paper moisture variation through drying length is a function of evaporation rate, machine speed, paper grammage and paper width which can be written as follow:

$$\frac{dH_p}{dx}=\frac{-N}{V\,G_{dry}\,W}(1+H_{p,out}) \tag{1}$$

where N represents the mass transfer rate or evaporation rate per unit length. H_p is paper moisture ratio. V, W and G_{dry} are machine speed, paper width and paper basis weight, respectively. x denotes paper length direction.

The temperature gradient in the paper length based on heat conservation equation can be presented as:

$$\frac{dT_p}{dx}=\frac{1}{\Gamma_f\,V\,C_p\,(1+H_p)}\times\left[Q_{in}-Q_{out}+N\,C_w\,T_p-N\,H_p\frac{dQ_s}{dH_p}\right] \tag{2}$$

Then:

$$\frac{dT_p}{dx}=\frac{1}{\Gamma_f\,V\,C_p\,(1+H_p)}\times[U_{sp}W\,(T_s-T_p)+U_{pa}W\,(T_a-T_p)-N\,(\lambda+Q_s)+N\,C_w\,T_p-N\,H_p\frac{dQ_s}{dH_p}] \tag{3}$$

here T_p, T_s and T_a represent paper, steam and pocket air temperature, respectively. Γ_f shows fiber mass per unit paper length. C_p and C_w are paper and water heat capacity, respectively. Q_{in} Q_{out} and Q_s are input and output energy and sorption heat, respectively. U_{sp} denotes overall heat transfer coefficient between steam inside cylinder and paper web per unit length.

Full details of formulation to develop the applied model and solve the algorithm of the main model equation can be found elsewhere [24].

3. Specifications of the studied paper machine

The studied paper machine (PM2) is located in Mazandaran wood and paper industry in Sari city which produces fluting paper. The paper web exits the press section with 55-60% moisture content and the remained water should be removed from the paper web in the drying section to the desired level (7-11%). The dryer section has 35 cylinders and it contains three drying groups, so that the first seven dryers belong to the steam group 1 and steam group 2 consists of dryers 8-18. Steam group 3 is the main group which consists of dryers 19-35. The dryer section has closed hood, rotary siphons and cascade steam system. The dryer is equipped with two heat recovery structures in the wet and dry end sections. The fresh supply air from outside is heated in two stages, at first it is heated with hood exhaust air and subsequently fresh steam is used to increase its temperature to the appropriate level for blowing into the drying pockets.

Main characteristics of the paper drying section which is used in this research are represented in the Table 1.

All physical properties of dry paper, i.e., moisture, grammage, caliper, … can be measured by experimental methods in accordance with standard procedures. Operational parameters of paper machine such as machine speed, web tension, steam pressure, total steam consumption and supply air temperature are measurable by local instruments and DCS. The temperature of the paper sheet is measured by IR-Thermometer and measuring the temperature of cylinder surface is carried out by surface thermometer. The dry and wet air temperatures are measured by proper thermometers. The available data measured by Metso Co. for web moisture content has been used in this research.

Properties of steam and air used in the studied paper dryer modeling are tabulated in the Tables 2 and 3, respectively.

4. Results and discussion

The results of applied model have been used to predict the main drying parameters, i.e., temperature and dryness of the paper web, temperature of cylinder surface, pocket dryer and exhaust air conditions and drying rate.

Table 1
Characteristics of the studied paper drying section.

Parameter	Value
Paper grade	Fluting
Typical basis weight (g/m^2)	127
Web speed (m/min)	406
Inlet dryness to drying section (%)	42.5
Inlet temperature (°C)	35
Paper width in drying section (m)	4.47
Web tension (kN/m)	2.5
Dry paper caliper (μm)	220
Dry paper heat capacity (J/kg.K)	1550
Dry paper conductivity (W/m.K)	0.08
Dry paper density (kg/m^3)	609
Total paper length in drying section (m)	145
Residence time of paper in drying section (s)	21.5
Fraction of cylinders contacting the web (%)	69

Table 2
Properties of steam in the studied drying section.

Parameter		Value
Header steam pressure (barg)		4
Header steam temperature (°C)		152
Steam pressure-G1 (barg)	Section 1	-0.03
	Section 2	-0.03
	Section 3	0.4
Steam pressure-G2 (barg)		3.4
Steam pressure-G3 (barg)		3.05

Table 3
Properties of air in the studied drying section.

Parameter		Value
Fresh supply and leakage air temperature (°C)		10
Supply and leakage air humidity (gwater/kg dry air)		16
Supply air mass flow rate (kg/s)	Wet end	11.7
	Dry end	11.8
Preheated supply air temperature (°C)	Wet end	35
	Dry end	38
Temperature of pocket drying air (°C)	Wet end	125
	Dry end	120
Exhaust air mass flow rate (kg/s)	Wet end	15.8
	Dry end	15.1
Exhaust air temperature (°C)	Wet end	84
	Dry end	87
Exhaust air humidity (g water/kg dry air)	Wet end	151
	Dry end	172
Leakage air mass flow rate (kg/s)		7.4
Hood balance (kg dry supply air/kg dry exhaust air)		0.76

4.1. Determination of mass and heat transfer coefficients

The main heat transfer resistances in the multi-cylinder paper drying consist of condensate inside the cylinder, cylinder shell, cylinder and paper surface interface, scale and fouling resistance and convective heat transfer of ventilation air.

According to the modeling results the mass and heat transfer coefficients for paper drying process in the considered drying section are represented in the Table 4. The correlating methods to determine the mass diffusivity, different heat and mass transfer coefficients have been previously represented [24].

Fig. 2 shows the contact heat transfer coefficient (h_{cp}) between cylinders and paper web surface and overall heat transfer coefficient between steam inside the cylinders and paper web (U_{sp}) for drying section. According to the Fig. 2, the U_{sp} and h_{cp} ranged between 212-472 and 559-1790 W/m^2.K, respectively.

4.2. Temperature and moisture prediction

The temperature profiles of the paper web and cylinder surface based on the modeling results have been shown in Fig. 3. The different drying phases have been clearly illustrated in Fig. 3. This Figure shows that the web temperature in the constant rate period containing the

Table 4
Mass and heat transfer coefficients based on the modeling results.

Parameter	Mean Value
Water and air diffusivity (m^2/s)	3.96×10^{-5}
Water-air mass transfer coefficient (m/s)	0.0254
Average condensate convective heat transfer coefficient inside dryer cylinder (W/m^2.K)	2270
Average contact heat transfer coefficient between the cylinder surface and the paper (W/m^2.K)	1187
Average overall heat transfer coefficient between steam and paper (W/m^2.K)	376
Average convective heat Transfer coefficient between paper and air (W/m^2.K)	18

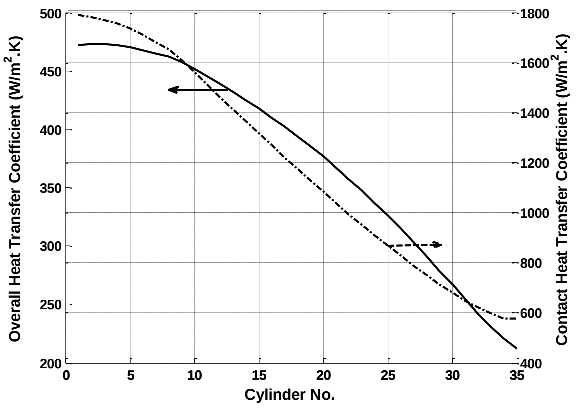

Figure 2. Contact and overall heat transfer coefficient over the dryer cylinders.

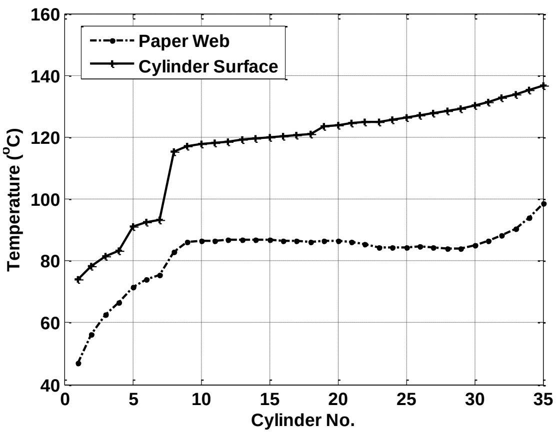

Figure 3. Temperature profile of the paper web and cylinder surface.

cylinders 8-30 is about 86°C and the paper exits the drying section with a temperature about 98°C. According to Fig. 3, the cylinder surface temperature rises gradually in the machine direction.

Fig. 4 shows the paper moisture profile in the studied drying section. As can be seen in Fig. 4, if the initial moisture content of paper is 57.5 %, the final web moisture of about 8% can be achieved at the end of the drying section. Moreover this Figure shows that the critical humidity of paper web at the end of the falling rate period (cylinder 30) is about 18%. Also, the evaporation mass flux rate or drying rate of the mentioned drying process has also been illustrated in Fig. 4. The

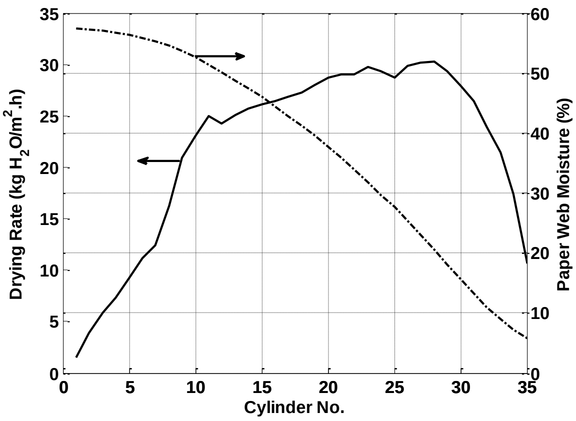

Figure 4. Variation of the paper moisture and drying rate in the machine direction.

calculated total evaporation and drying rates are about 4.52 kg/s and 22 kg/m^2.h, respectively.

4.3. Effect of web tension on the drying heat transfer

The humid paper web is held strongly against the drying cylinders by a synthetic permeable felt called dryer fabric. The main task of the fabric is to support and transport the paper web through the drying section [25]. Moreover, the mechanical contact pressure by means of dryer fabric tension is also used to press the web onto the cylinders to obtain a better thermal contact surface and therefore to provide improved heat transfer coefficient [5,26]. A boundary layer of air and evaporated water is formed between the paper and dryer cylinder surface. This boundary layer reduces the overall heat transfer in the drying section. The appropriate tension level is required to decrease the boundary layer thickness [27]. The air thickness between the cylinder and web surface can be calculated as follows [28]:

$$t_a = 1.51 D_c \left(\frac{3\pi\sqrt{2}\ \mu_a V}{4\,\tau_{eff}}\right)^{2/3} \quad (4)$$

where μ_a and t_a represent air viscosity and air boundary layer thickness, respectively. V denotes web speed and D_c is drying cylinder diameter. τ_{eff} represents the effective tension of the drying fabric which can be computed by the following relation:

$$\tau_{eff} = \tau - V^2 . G_t \quad (5)$$

here, τ is the fabric operational tension and G_t denotes the basis weight of the paper and fabric. In the studied drying section with a web tension of about 2.5 kN/m, the thickness of air boundary layer over the drying cylinders varied between 71 and 77 μm.

Accordingly the heat transfer coefficient using the concept of the theoretical air gap has been estimated by Riddiford as follows [29]:

$$h_{cp-dry} = \frac{(0.0222 T_a + 7.18) \times 10^{-3}}{R_c \, (\frac{\mu_a V}{\tau})^{2/3}} \quad (6)$$

where h_{cp-dry} and R_c represent contact heat transfer coefficient of dry paper and cylinder radius, respectively.

The moisture content of the paper web is not included in the equation (6), hence this correlation can be applied for dry paper with appropriate accuracy. Based on the equation (6) the contact heat transfer coefficient (h_{cp}) between cylinders and paper web surfaces and overall heat transfer coefficient between steam and paper web (U_{sp}) against the various web tensions are represented in Fig. 5. If the web tension varies from 1 to 5 kN/m (the operating range of the studied machine), the air gap thickness will be in the range of 45-140 μm and the overall mean heat transfer coefficient will be approximately within 300-550 W/m^2.K.

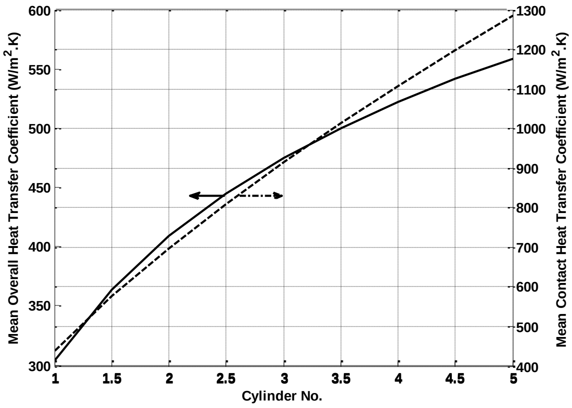

Figure 5. Effect of web tension on the contact and overall heat transfer coefficients.

4.4. Determination of energy indicators

The energy performance of a drying process is defined by various indices which commonly differ depending on the type and configuration of paper machine, paper grade, geographic situation and other parameters [5]. The modeling results of energy performance for studied paper machine drying section are presented in Table 5.

According to Table 5, the energy indices and energy efficiency of the drying section is relatively acceptable in comparison with other similar machines, but the heat recovery system has a low efficiency.

4.5. Thermodynamic analysis of pocket drying section

The absolute and relative humidity of the pocket drying air can be computed based on its partial pressure and temperature:

$$AH = \frac{M_w}{M_a}\frac{P_w}{P_a} = 0.622 \frac{P_w}{P_t - P_w} \quad (7)$$

$$RH = \frac{P_w}{P_w^{sat}} \times 100 \quad (8)$$

$$AH = \frac{0.00622 RH . P_w^{sat}|T_a}{P_t - 0.01 RH . P_w^{sat}|T_a} \quad (9)$$

where *AH* and *RH* represent the absolute

Table 5
Various energy performance indices in studied drying section.

Parameter		Value
Steam consumption (ton/h)	Drying cylinders	19.44
	Heat recovery system	3.49
Specific Steam Consumption per produced paper (SSC_{paper}) (kg steam/kgpaper)		1.66
Specific Steam Consumption per evaporated water (SSC_{water}) (kg steam/kg water)		1.4
Specific Heat Consumption per produced paper (SHC_{paper}) (GJ/ton paper)		4.59
Specific Heat Consumption per water evaporation (SHC_{water}) (GJ/ton water)		3.96
Dryer thermal efficiency (%)		60
Average efficiency of heat recovery system (%)		4.3

humidity and relative humidity of pocket air, respectively. T_a and P_t denote the temperature and total pressure of the pocket air, respectively. P_w is partial pressure of water in the pocket air and P_w^{sat} is saturated vapor partial pressure for free water given by Antoine's equation [23]:

$$P^{sat} = 10^{7.074 - \frac{1657.46}{T_a + 227.02}} \tag{10}$$

The evaporated water increases the hood humidity; accordingly the humidity of exhaust air can be calculated as follows:

$$X_{ea} = \frac{\dot{m}_{ev}}{\dot{m}_{ea}} + X_{sa} = \frac{\dot{m}_{ev} \times HB}{\dot{m}_{sa}} + X_{sa} \tag{11}$$

here X_{pd} is the exhaust air absolute humidity. $\dot{m}_{ev}$ denotes the evaporation rate. $\dot{m}_{sa}$ and $\dot{m}_{ea}$ are the mass flow rate of the dry supply and dry exhaust air, respectively. HB is the ratio of the supply air to the exhaust air named hood balance. The exhaust humidity variations against the changes of the supply air mass rate are represented in Fig. 6.

An important parameter in the paper drying process is the dew point. It is necessary that no condensation takes place within the drying hood and pocket ventilation area. Therefore the humidity of the pocket drying air must be lower than the paper web and the temperature should be maintained above the dew point [26]. In the higher dew point, the drying air can contain more vapors which could lead to the reduction of ventilation air. Furthermore, at higher dew point temperatures, higher heat recovery from the exhaust air can be achieved.

The dew point temperature (T_{dp}) can be calculated as follows [30]:

$$T_{dp} = 99.64 + 329.64 \frac{\ln\left(\frac{P_{va}}{100}\right)}{11.78 - \ln\left(\frac{P_{va}}{100}\right)} \tag{12}$$

here, P_{va} is the vapor partial pressure of the pocket air, which is given by Eq. (13).

$$P_{va} = P^{sat} \,.\, RH \tag{13}$$

Common dew point temperature in the paper mill drying section is 59°C. Whereas some paper mills have dryers with operating dew point higher than 62°C, paper mills with closed hoods often

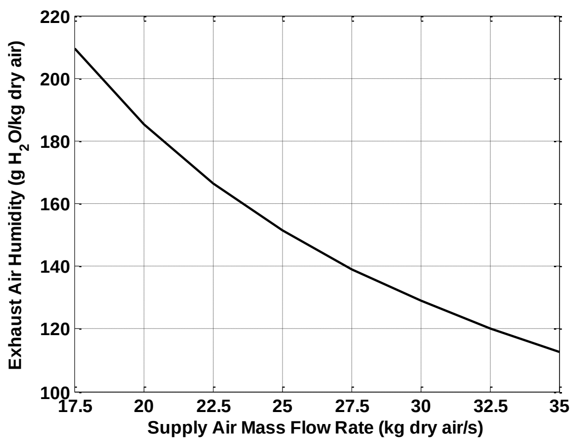

Figure 6. The exhaust hood humidity versus the supply air mass rate.

operate on dew points near 55°C or lower [4]. Increasing the dew point level to a higher value can decrease the energy use per kg of water evaporation. According to the design documents, the air humidity level in the pocket dryers, for two tier configuration, should be lower than 250 gH_2O/kg dry air [31,32].

Based on the modeling results, the humidity changes for 35 pocket dryers are illustrated in the Fig. 7. As seen in the Fig. 7, the pocket dryer humidities in the cylinders 9-17 exceeded the maximum allowable range which is typically concerned with the fabric cleanliness or inequity of the supply air.

According to the modeling results, the average humidity of the exhaust air in the drying hoods can be appropriately predicted to be about 161 g H_2O per kg dry air which has a dew point temperature around 60°C.

The variations of dry and dew temperatures in the pocket dryers are shown in the Fig. 8.

As shown in the Fig. 8, dew drop never happened during the dryer section. The pocket air temperatures were between 50 and 90°C. The dew point temperatures were not close to the pocket air temperature, differing by about 10-42°C. The minimum temperature difference occurred at cylinder #35 (10°C).

Table 6 represents the design, operating and maximum allowable level for absolute and relative humidity, dry temperature and dew point of exhaust air.

The humidity of hood exhaust air for original evaporation level (4.17 kg/s) was 0.136 kg H_2O/kg dry air. As can be seen in Table 6, the current operating humidity of

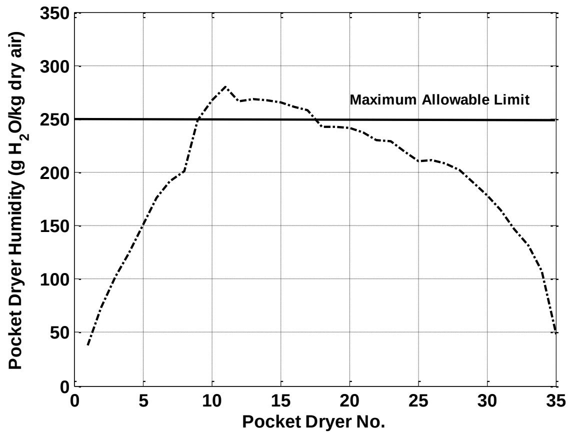

Figure 7. The humidity variation of pocket dryers in the studied drying section.

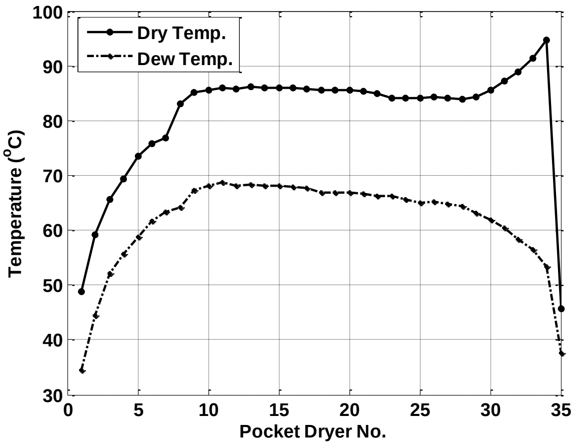

Figure 8. The variation of dry and dew temperature in the pocket dryers.

the exhaust hood has increased in comparison with the deign level due to today's higher evaporation. The evaporation level is now ~8 % higher than the original level. Thus based on the equation 11, the supply air mass flow rate should be increased to about 28.5 kg/s. Accordingly the exhaust air mass rate can reach to about 37.5 kg/s. It means around 21% extra exhaust capacity is required to maintain the exhaust humidity to the level. Exhaust air humidity can be computed by the following relation, too:

Table 6
The exhaust air properties for design and operating conditions.

Parameter	Value				
	Design	Wet end	Dry end	Average	Maximum Allowable level
Absolute humidity (g H_2O/kg dry air)	136	151	172	161	250
Dew point temperature (ºC)	58	59	61	60	68
Dry temperature (ºC)	80	84	87	85	95
Partial humidity (%)	36	34.5	34	35	33

$$X_{ea} = \frac{\sum_{pd=1}^{35} (X_{pd}\,\dot{m}_{sa}) + X_{sa}(\dot{m}_{sa} + \dot{m}_{la})}{\dot{m}_{ea}} \quad (14)$$

here X_{pd} is the humidity level of surrounding air in the pocket drying zone. So the highest allowable level of the exhaust air humidity can be estimated as follows:

$$X_{ea,\max} = HB \times X_{pd,\max} + X_{sa} \quad (15)$$

$X_{pd,\max}$ represents the maximum humidity of the pocket drying air that as mentioned, should not exceed 250 g H_2O/kg dry air in double-felted areas [31]. Hence the maximum level for the exhaust air in the investigated conditions can be estimated to be about 0.2 kg H_2O/kg dry air. Also, according to guidelines of the Technical Association of the Paper and Pulp Industry (TAPPI), the absolute humidity of the pocket air should be less than 0.2 kg water /kg dry air [23]. Consequently the required theoretical supply and exhaust air to keep the exhaust humidity to this level can be predicted to be about 19 kg/s and 25 kg/s which can lead to a 20% reduction in the air usage. The dew point of the exhaust air in this humidity will be around 64°C which is about 4°C above the current value. Raising the moisture content and dew temperature of the exhaust air can reduce the energy consumption and cause the exhaust heat recovery potential to increase.

As can be seen from Fig. 9, the specific heat consumption per evaporated water (SHC_{water}) for the studied drying section can be reduced from 3.96 to 3.81 GJ per ton water (around 4% reduction), due to increasing the exhaust air humidity.

Also, Fig. 10 shows that the higher exhaust air humidity causes higher heat recovery potential in the drying section. As can be seen from this figure, the heat recovery potential for each kg of dry air can be increased around 20% by increasing the exhaust humidity to the maximum allowable level.

5. Conclusions

In this study a developed model has been utilized to evaluate the thermodynamic conditions of the pocket drying and hood exhaust air and heat recovery performance

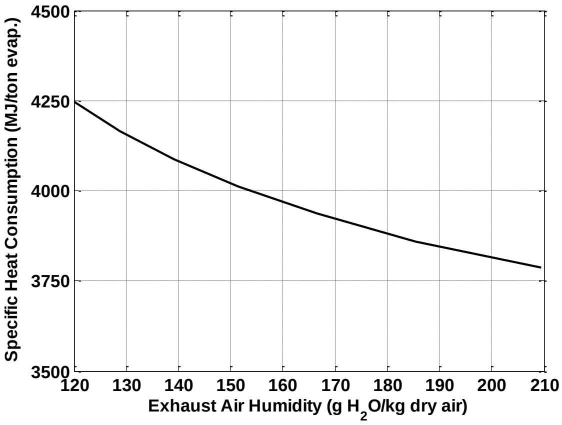

Figure 9. The specific heat consumption at various exhaust air humidity.

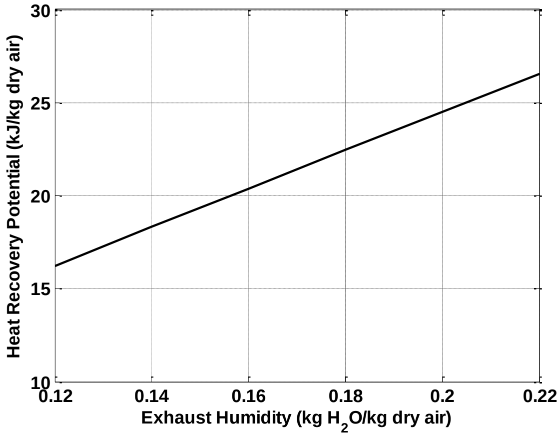

Figure 10. The heat recovery potential at various exhaust air humidity.

in the drying section of the paper machine which produces fluting or corrugating paper. Also, the influences of the web tension changes on the air boundary layer thickness and contact heat transfer resistance have been investigated, as well.

Results show that by increasing the web tension from 1 to 5 kN/m, the air gap thickness varies from 45-140 μm and accordingly the overall mean heat transfer coefficient will be within 300-550 $W/m^2.K$.

The steam usage for the considered drying section was around 1.66 kg per kg paper and the specific energy consumption per production has been determined to be about 3.96 GJ/ton paper.

The pocket dryer properties for the studied drying section have been evaluated. Maximum humidity of the pocket drying air should be lower than 0.25 kg H_2O/kg dry air and thus the maximum level for the exhaust air in the studied machine can be estimated to be 0.2 kg H_2O/kg dry air. The pocket air temperature was not close to the dew point temperature, differing by almost 10-42°C and dew drop never happened during the dryer section. The pocket air temperature was between 50 and 90°C.

According to the modelling results for the studied drying section, increasing the exhaust air humidity to the highest permissible level will result in around 4% reduction in the specific heat consumption per evaporated water (SHC_{water}) and 20% rise in the heat recovery potential for each kg of water.

The maximum level for the exhaust air in the studied machine can be estimated to be 0.2 kg H_2O/kg dry air. Results show that by increasing the exhaust air humidity to the highest allowable level, the supply air consumption can be reduced to around 20% which will lead to a 4% reduction in the required energy in the heat recovery section.

Acknowledgements

The authors would like to thank the Sahand University of Technology for the financial support of this work. The Fluting mill of Mazandaran Wood and Paper Industries (MWPI) is also gratefully acknowledged for providing helpful industrial data.

Nomenclature

AH	Absolute humidity (kg H_2O/kg dry air)
C	Heat capacity (J/kg.K)
G	Basis weight or Grammage (kg/m^2)
HB	Hood balance (kg dry supply air/kg dry exhaust air)
H_p	Paper moisture ratio (kg H_2O/kg fiber)
h_{cp}	Contact heat transfer coefficient between cylinder surface and paper web (W/m^2.K)
$\dot{m}_{ev}$	Mass evaporation rate (kg/s)
M	Molecular weight (kg/mol)
N	Mass transfer rate or evaporation rate per unit length (kg/m.s)
P	Pressure (kPa)

P^{sat}	Saturated pressure (kPa)
Q	Transferred Energy (W)
Q_s	Heat of sorption (J/kg)
R	Radius (m)
RH	Relative humidity (%)
T	Temperature (˚C)
t	Thickness (m)
U_{sp}	Overall heat transfer coefficient between steam inside cylinder and paper web per unit length (W/m)
U_{pa}	Heat transfer coefficient between paper and surrounding air per unit length (W/m)
V	Web speed (m/s)
W	Paper width (m)
λ	Latent heat (J/kg)
μ	Viscosity (kg/m.s)
τ	Web tension (N/m)
τ_{eff}	Effective web tension (N/m)
Γ	Mass per unit paper length (kg/m)
	Subscripts
a	air
c	cylinder
d	dry air
dp	dew point
dry	dry paper
ea	exhaust air
ev	evaporation
f	fiber
in	input
la	leakage air
out	output
p	paper
pa	paper - air
pd	pocket dryer
s	steam
t	total
sa	supply air
sp	steam-paper
v	vapor
w	water

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