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SHORT COMMUNICATION

Modeling of the Drying Process in Paper Plants

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Abstract−In this study a model for the drying process in paper production plants was developed based on the mass and heat balances around drying cycles. Relationships for the heat transfer coefficients between the web and the air as well as between the drying cylinder and the web were extracted from the closed-loop plant operation data. It was found that the heat transfer coefficients could be represented effectively in terms of moisture content, basis weight and reel velocity. The effectiveness of the proposed model was illustrated through numerical simulations. From the comparison with the operation data, the proposed model represents the paper plant being considered with sufficient accuracy.

Key words: Paper Mill, Drying Cylinder, Heat Transfer Coefficient, Simulation, Bone-dry Weight

INTRODUCTION

The purpose of the drying process in a paper production plant is to supply sufficient heat to each dryer in order to dry the wet paper web up to the desired moisture content. Steam is the major heat source in most cases. It is likely that the steam-heated cylinders will continue to provide a significant fraction of the paper drying needs in the future. The steam fed into drying cylinders is condensed into water releasing heat. In order to increase the drying efficiency and the production volume, it is indispensable to supply an adequate amount of steam into the drying cylinders and to exhaust the condensate being produced in each dryer. Due to the complexity of the paper drying process, improvement of process performance in the operation of the drying process has been a challenging problem. Without exact knowledge of the cylinder temperature and water content in the moving web, optimal operation may be difficult to achieve.

Utilization of a plant model in the operation is one of the most promising ways to improve plant performance [Yeo et al., 2003; Arpornwichanop et al., 2002; Yoo et al., 2004; Yu and Sosna, 2001]. To be of practical use, a model must be sufficiently complete so that it can include all the important effects to which the wet web is exposed as it travels through the drying section. Modeling of the drying process in paper machines has attracted the attention of many researchers. About three decades ago an analog computer model for paper drying processes was proposed [Depoy, 1972]. In this model, simple linear relationships representing heat capacity, thermal conductivity and heat transfer coefficient as well as density were used. An interesting iron model was reported [Mori et al., 2000] to be used in the control operation during paper grade changes. In this model, empirical relationships concerning evaporation rate and steam prediction were employed with heat transfer coefficients being kept constant. A state model for the paper drying process in a paperboard mill was presented [Berrada et al., 1997]. After linearization, this model could be represented in the familiar state-space form for use in control. Fundamental knowledge concerning drying of web, operation of drying machine and important auxiliary systems was provided [Karlsson, 1984, 2000]. Identification of heat transfer coefficients has been the key issue in the modeling of the paper drying process. Without any means of detecting heat transfer coefficients directly, we can rely only on the empirical relationships describing heat transfer coefficients. But any reliable representation for heat transfer coefficients has not been reported yet.

The objective of the present study was to develop a dependable model for the drying process in paper production plants. A relationship for the heat transfer coefficient was extracted from the closed-loop plant operation data. It was found that the heat transfer coefficient could be represented effectively in terms of moisture content, basis weight and reel velocity. Effectiveness of the proposed model is illustrated through numerical simulations.

MODELING OF THE DRYING PROCESS

Fig. 1 shows the schematic of the dryer section configuration. There are 55 drying cylinders in the drying section of the plant being considered. The first 39 cylinders form the main-dryer section and the remaining cylinders compose the after-dryer section. Each dryer section is divided into several groups according to the steam pressure being applied. In the paper plant considered in the present study, the main-dryer section consists of 3 groups and the after-dryer section consists of 2 groups as shown in Table 1. The dynamics of a single drying cylinder and the paper sheet during an altered valve position are presented [Karlsson, 2002].

The multi-cylinder drying process consists of repeated cycles in the direction of wet web travel. Each cycle has different phases depending upon the dryer configuration. Fig. 2 shows the drying cycle of the 1st group with notation where steam is not supplied into the lower cylinder denoted by C'-D where the web remains in contact with the cylinder covered on its outer surface by the canvas as well as in the free-run. Fig. 3 shows the drying cycle with double-felted configuration where the web remains in contact with the cylinder covered on its outer surface by the canvas but is no longer covered

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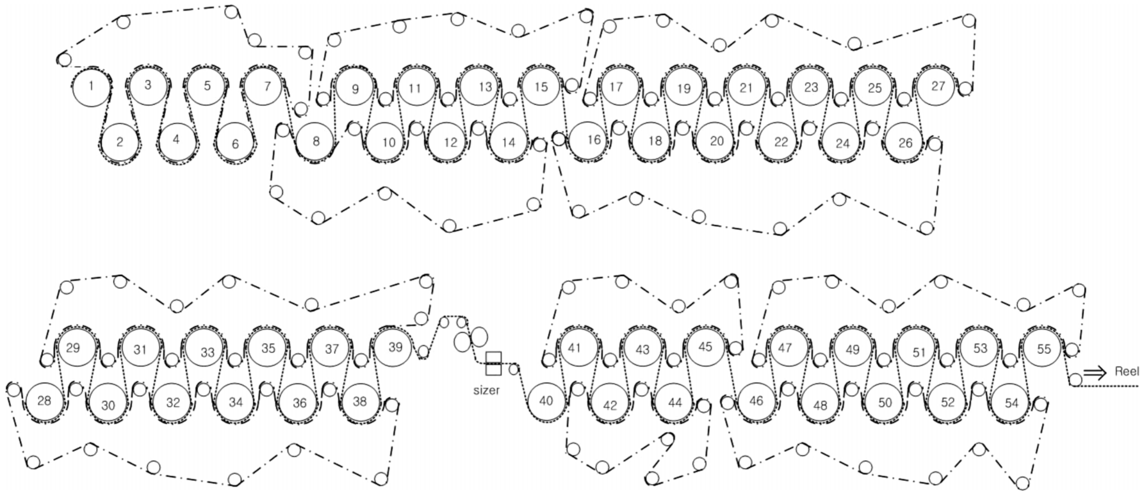

Fig. 1. Schematic of dryer section configuration.

Table 1. Cylinder groups in the dryer section

Section	Group number	Cylinder number	Remarks
Main dryer	1	1-7	Steam is not supplied into the cylinder 1, 2, 4 and 6
	2	8-15	
	3	16-39	
After dryer	4	40-45	
	5	46-55	

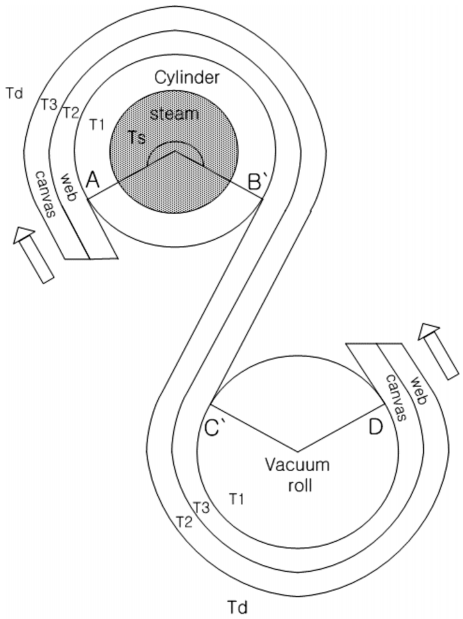

Fig. 2. Drying cycle of the 1st group.

with the canvas in the free-run.

The formulation of the dryer model is based on heat and mass balances. These balances consist of sets of differential equations describing heat and mass transfer around the canvas, the web and the drying cylinder. It is assumed that the steam inside the cylinder

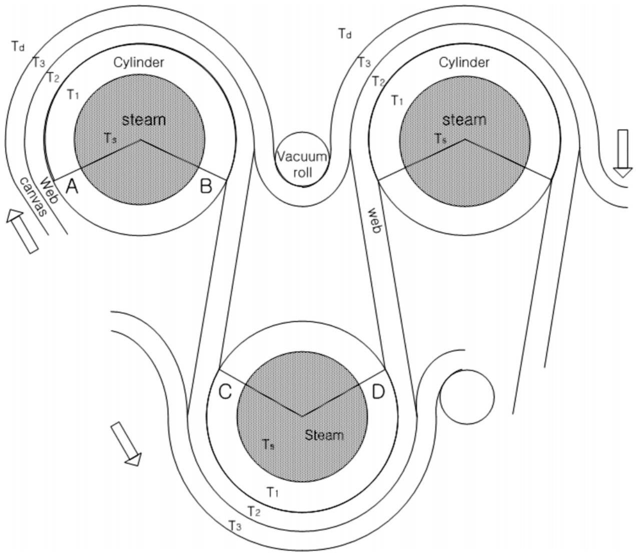

Fig. 3. Drying cycle with double-belted configuration.

is saturated and the temperature inside the canvas and the web is uniform. The resistance caused by the material characteristics of the wet web and the canvas on heat transfer and evaporation is also assumed to be negligible.

In the zone A-B, the behavior of the cylinder temperature can be written as

$$\frac{dT_1}{dt}=\frac{1}{L_D\rho_D C_D}\{h_s T_s-(h_s+h_{dw})T_1+h_{dw}T_2\} \tag{1}$$

From the balance around the web we have

$$\frac{dT_2}{dt}=\frac{1}{D(1+a_w)C_w}\{h_{dw}T_1-(h_{dw}+h_{wc})T_2+h_{wc}T_3-m^*\Delta Hev\} \tag{2}$$

where the specific heat of the web is given by

$$C_w=\frac{0.32-1.366a_z+a_w}{1+a_w} \tag{3}$$

The evaporation rate m from the web can be expressed as

$$m=\frac{h_e}{C_a+x_s\cdot C_v}(x_s-x) \quad (4)$$

where the air moisture x_v and x are given by

$$x_s=\frac{0.62197\cdot P_s}{P-P_s} \text{ and } x_v=\frac{0.62197\cdot P_w}{P-P_w} \quad (5)$$

$$x=\frac{1.0048(T_w-T_d)+x_v(2501-2.3237\cdot T_w)}{2501+1.86\cdot T_d-4.19\cdot T_w} \quad (6)$$

The vapor partial pressures P_s and P_w are given by Antoine's equation as

$$P_w=10^{5.11564-\frac{1687.537}{T_w+230.17}} \text{ and } P_s=10^{5.11564-\frac{1687.537}{T_{we}+230.17}} \quad (7)$$

The heat of evaporation is the sum of the latent heat of vaporization for free water and the heat of sorption, i.e.,

$$\Delta H_{ev}(\text{heat of evaporation})=\Delta h_{vap}(\text{latent heat of vaporization}) +\Delta h_s(\text{heat of sorption}) \quad (8)$$

where the latent heat of vaporization is given by

$$\Delta h_{vap}=505.3747(1-T_r)^{0.354}+269.6581(1-T_r)^{0.456} \quad (9)$$

The reduced temperature is defined by

$$T_r=\frac{T_{we}}{T_c}=\frac{T_{we}}{373.95}(T_{we}:\ ^{o}C) \quad (10)$$

The sorption isotherm of a paper web depends on its composition. Filler content has a prominent influence on sorption properties. Various correlations for sorption isotherms are available in the literature. Calculated sorption heat values depend on the mathematical formula and data used in the calculations. This can result in unrealistic values and large variation in the computed sorption heat values. A correlation for the sorption isotherm [Karlsson, 2000] can be effectively used to express the heat of sorption. A useful relation was derived in terms of the relative humidity of the air and the moisture content as given by

$$\Delta h_s=-R\left(\frac{1-\varphi}{\varphi}\right)\cdot 0.10085\cdot a_w^{1.0585}\cdot T_{we}^2 \quad (11)$$

The relative humidity of the air can be written as

$$\varphi=1-\exp[-47.58\times a_w^{1.877}-0.10085\times T_{we}\times a_w^{1.0585}] \quad (12)$$

By combining above relations, we can finally represent the heat of evaporation as

$$\Delta H_{ev}=505.3747\left(1-\frac{T_{we}}{373.95}\right)^{0.354}+269.6581\left(1-\frac{T_{we}}{373.95}\right)^{0.456} +0.011124\left(1-\frac{1}{\varphi}\right)a_w^{1.0585}\times T_{we}\times(T_{we}+273.15) \quad (13)$$

From the balance around the canvas we have

$$\frac{dT_3}{dt}=\frac{1}{L_c\rho_c C_c}\{h_{wc}T_2-(h_{wc}+h_e)T_3+h_eT_d\} \quad (14)$$

In the zone B-C, the dynamics of the web temperature and the moisture content are given by

$$\frac{dT_2}{dt}=\frac{1}{D(0.32-1.366a_z+a_w)}\{2*h_e(T_d-T_2)-2\cdot m*\Delta Hev\} \quad (15)$$

$$\frac{da_w}{dt}=-2*\frac{m}{D} \quad (16)$$

In this zone evaporation occurs on both sides of the web. In the zone B'-C', where the web remains in contact with the canvas on one side in the free-run, energy balances around the web and the canvas give

$$\frac{dT_2}{dt}=\frac{1}{D(0.32-1.366a_z+a_w)} \{h_e*T_d-T_2(h_e+h_{wc})+h_{wc}T_3-2\cdot m*\Delta Hev\} \quad (17)$$

$$\frac{dT_3}{dt}=\frac{1}{L_c\rho_c C_c}\{h_{wc}T_2-(h_{wc}+h_e)T_3+h_eT_d\} \quad (18)$$

In the computation of the modeling equations, determination of the heat transfer coefficients is the most important task. It is known that these coefficients depend upon the moisture content and the web travel speed [Karlsson, 2000]. But any explicit expression has not been reported so far. An empirical expression for the heat transfer coefficient between the web and the air at the free-run in terms of the travel speed has been reported [Mori et al., 2000]. But, in most cases, values of heat transfer coefficients have been assumed to be constant. Selection of the constant has relied on the operational experience or was based on the experimental results for similar situations.

The heat transfer coefficients between the web and the air as well as between the drying cylinder and the web have a strong influence on the dynamics of the moisture and the temperature at each cylinder. In this work we developed a relation that correlates the heat transfer coefficient with the basis weight, the reel speed and the moisture content of the web. For the main-dryer section, the relations for h_{dw} and h_e developed in the present work have the form

$$h_{dw}=c_1 * \exp(c_w * a_w)+c_3 * \exp(c_4 * a_w) \quad (19)$$

$$h_e=k_1 * BW * V^n * \exp(k_2 * BW * V^n * a_w) +k_3 * BW * V^n * \exp(k_4 * BW * V^n * a_w) \quad (20)$$

The values of the parameters c_i, k_i and n are dependent upon the specific paper machine being used. The relation for h_{dw} for the after-dryer section has of the form

$$h_{dw}=c_1 * a_w^3+c_2 * a_w^2+c_3 * a_w+c_4 \quad (21)$$

The relation for h_e for the after-dryer section has the same form as in the main-dryer section. The heat transfer coefficient h_s between the steam and the cylinder body and h_{wc} between the web and the canvas do not show significant variations during operation and they were assumed to be constant. Table 2 shows values of the parame-

Table 2. Parameters for heat transfer relations

Parameter	Main-dryer	After-dryer
c_1	0.1661	19.09
c_2	1.512	−6.489
c_3	−0.4775	1.167
c_4	−15.67	0.1684
k_1	0.0231	0.0085
k_2	0.4243	3.103
k_3	−0.008	−0.0053
k_4	−14.67	−100.63
n	0.518	0.52

Table 3. Data for simulations

Description	Basis weight (g/m^2)		
	55	70	82
Reel speed(m/min)	904	892	901
Ash content(%)	18	17	18
Amount of sizing(g)	2	3	2.5
Sizing consistency(%)	19	16.5	19
Moisture content at the main-dryer outlet (%)	8.5	8.5	8.5
Moisture content at the after-dryer outlet (%)	3	5.5	2.5
Steam to the cylinder 3 (kg/cm^2)	0.3673	0.1296	0
Steam to the cylinder 5 (kg/cm^2)	0.3673	0	0.1
Steam to the cylinder 7 (kg/cm^2)	0.3673	0.82	0.1
Steam to the 2^{nd} group (kg/cm^2)	0.964	1.425	1.2
Steam to the cylinder 1 of the 3^{rd} group (kg/cm^2)	1.4812	1.885	1.8
Steam to the cylinder 2 of the 3^{rd} group (kg/cm^2)	0.5129	0.453	1.2
Steam to the 4^{th} group (kg/cm^2)	0.902	0.88	1.6
Steam to the 5^{th} group (kg/cm^2)	0.902	0.88	1.6
Cylinders without steam supply	1, 15, 21-25, 29-37, 41,51-53	1, 19, 21-25, 29-35, 49-52	1, 34-37, 40, 41, 53

ters for the plant being considered in the present study.

SIMULATIONS

Several simulations were performed to validate the model developed in the present study. Three typical paper grades, the basis weights of which are 55, 70 and 82 g/m^2, were selected. Operating conditions for these papers were used in the simulations, and operation data during the production of these papers were collected for the purpose of comparison with simulation results. Table 3 shows operating data used in the production of those papers as well as in the simulations.

Fig. 4 shows results of simulations for the main-dryer with h_e being kept constant for the paper with the basis weight of 55 g/m^2. As mentioned before, constant heat transfer coefficients have been used in most of the drying models reported so far. The significant discrepancy between plant data and simulation results as can be seen in Fig. 4 demonstrates the inadequacy of the use of constant heat transfer coefficients. In the present model numerical values of the heat transfer coefficients for each drying cylinder were obtained from (19), (20) and (21) with the parameter values given in Table 2. Results of simulations for the main-dryer using the updated heat transfer coefficients are shown in Fig. 5 for the paper with the basis weight of 55 g/m^2. As can be seen in Fig. 5, the model tracks the measured operation data closely and we can validate the effectiveness of the present model. Figs. 6 and 7 show similar results for the main-dryer for the paper with a basis weight of 70 g/m^2. Again, the model expresses the plant with sufficient accuracy.

For the after-dryer, no appreciable modeling results have been reported and we applied variable heat transfer coefficients given by (20) and (21) with the parameter values given in Table 2. Results of simulations are shown in Fig. 8 for the paper with a basis weight

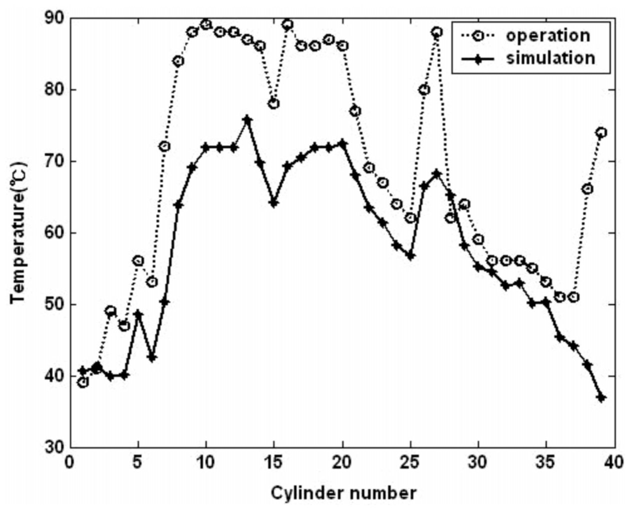

Fig. 4. Main-dryer temperature profile : constant heat transfer coefficients (basis weight: 55 g/m^2).

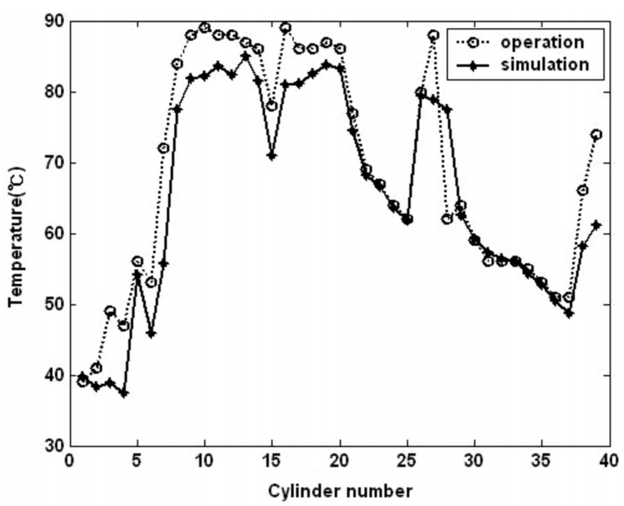

Fig. 5. Main-dryer temperature profile : variable heat transfer coefficients (basis weight: 55 g/m^2).

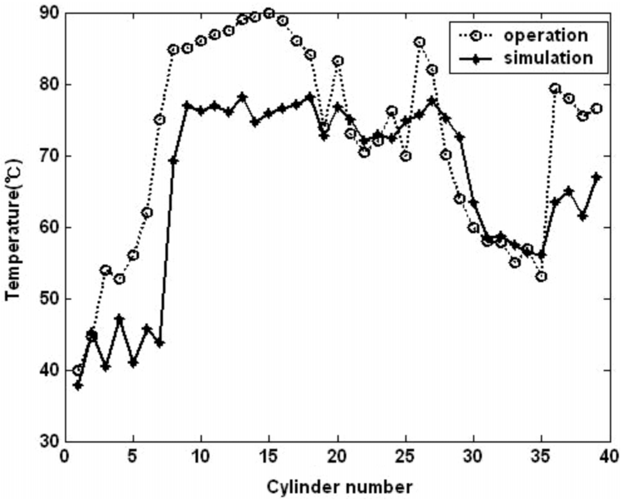

Fig. 6. Main-dryer temperature profile: constant heat transfer coefficients (basis weight: 70 g/m²).

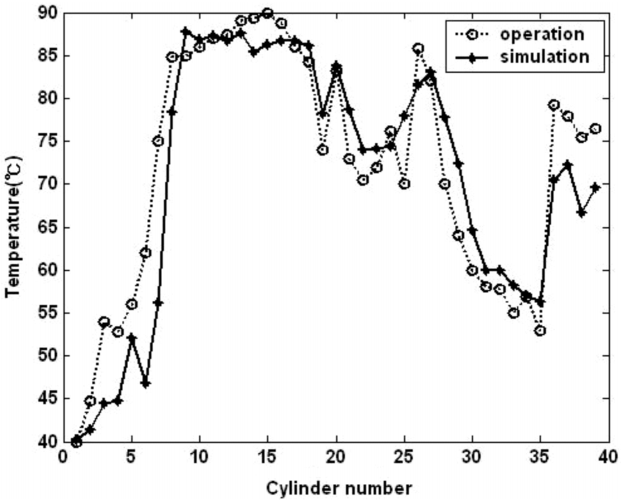

Fig. 7. Main-dryer temperature profile: variable heat transfer coefficients (basis weight: 70 g/m²).

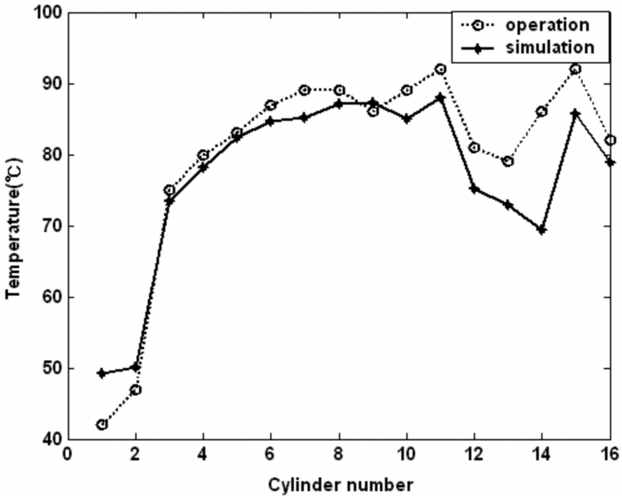

Fig. 8. After-dryer temperature profile: variable heat transfer coefficients (basis weight: 55 g/m²).

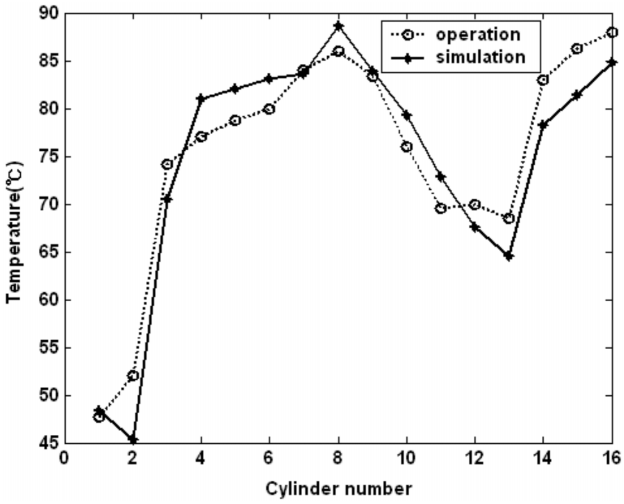

Fig. 9. After-dryer temperature profile: variable heat transfer coefficients (basis weight: 70 g/m²).

of 55 g/m² and Fig. 9 for the paper with a basis weight of 70 g/m². It is clear that the after-dryer section can also be expressed well by the model proposed.

Variation of the moisture content of the web traveling through the drying section is another major concern of the operational engineers. The quality of the paper produced depends on the final moisture content. In fact, the objective of the drying process is to meet the specification on the moisture content for the specific paper grade.

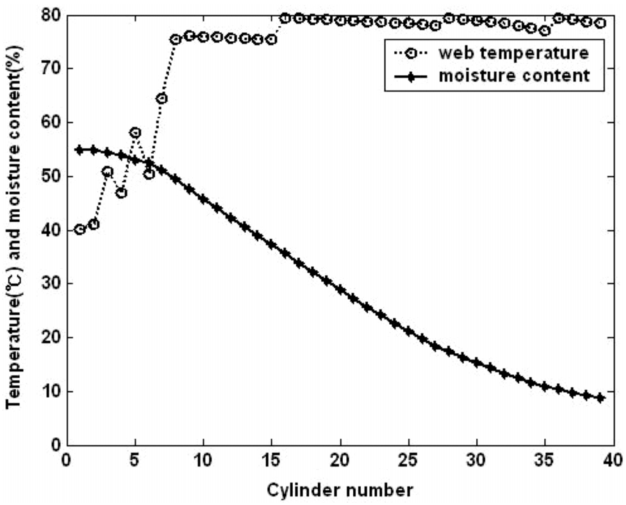

Fig. 10. Main-dryer moisture content: variable heat transfer coefficients (basis weight: 82 g/m²).

Table 4. Moisture content at the outlet of main- and after-dryer

Basis weight (g/m²)	Main-dryer		After-dryer	
	Operation (%)	Simulation (%)	Operation (%)	Simulation (%)
55	8.5	8.51	3.0	2.91
70	8.5	8.43	5.5	5.37
82	9.0	8.82	2.5	2.43

Fig. 10 shows the profile of the moisture content for the paper with the basis weight of 82 g/m^2. The web temperature shown in Fig. 10 is the temperature of the web in the free-run zone. The moisture contents at the end of the main-dryer and after-dryer are summarized in Table 4. We can see that the proposed model predicts the moisture content at each dryer section with sufficient accuracy.

CONCLUSION

A model for the drying process in paper production plants was developed based on the mass and heat balances around drying cycles. The heat transfer coefficients between the web and the air as well as between the drying cylinder and the web have a strong influence on the dynamics of the moisture and the temperature at each cylinder. Relationships for these heat transfer coefficient were extracted from the closed-loop plant operation data. It was found that the heat transfer coefficients could be represented effectively in terms of moisture content, basis weight and reel velocity. The effectiveness of the proposed model was illustrated through numerical simulations. From the comparison with the operation data, the proposed model represents the paper plant being considered with sufficient accuracy.

NOMENCLATURE

a_w : web moisture content
a_z : ash ratio
BW : basis weight [kg/m^2]
C_a : specific heat of dry bulb air [kcal/kg °C]
C_c : specific heat of canvas [kcal/kg °C]
C_D : specific heat of cylinder [kcal/kg °C]
C_v : specific heat of vapor [kcal/kg °C]
C_w : specific heat of web [kcal/kg °C]
D : bone-dry weight [kg/m^2]
h_{dw} : heat transfer coefficient between the cylinder and the web [$kcal/m^2$ sec °C]
h_e : heat transfer coefficient between the web and the air [$kcal/m^2$ sec °C]
h_s : heat transfer coefficient between the steam and the cylinder [$kcal/m^2$ sec °C]
h_{wc} : heat transfer coefficient between the web and the canvas [$kcal/m^2$ sec °C]
ΔH_{ev} : heat of evaporation [kcal/kg]
Δh_s : heat of sorption [kcal/kg]
Δh_{vap} : latent heat of vaporization [kcal/kg]
L_C : thickness of canvas [m]
L_D : thickness of cylinder [m]
m : evaporation rate [kg/m^2 sec]
R : gas constant [kcal/kg molK]
P : total pressure [bar]
P_s : vapor partial pressure on the web surface [bar]
P_w : vapor pressure in the surrounding air [bar]
T_d : dry bulb temperature of air [°C]
T_s : steam temperature [°C]
T_w : wet bulb temperature of air [°C]
T_{we} : temperature of web [°C]
x : air humidity in the surrounding air [kgH_2O/kg dry air]
x_s : air humidity at the web surface [kgH_2O/kg dry air]
x_v : air moisture [kgH_2O/kg dry air]

Greek Letters

ρ_C : density of canvas [kg/m^3]
ρ_D : density of cylinder [kg/m^3]
φ : relative humidity of air

REFERENCES

Arpornwichanop, A., Kittisupakorn, P. and Hussain, M. A., "Model-Based Control Strategies for a Chemical Batch Reactor with Exothermic Reactions," *Korean J. Chem. Eng.*, **19**(2), 221 (2002).

Berrada, M., Tarasiewicz, S., Elkadiri, M. E. and Radziszewski, P. H., "A State Model for the Drying Paper in the Paper Product Industry," *IEEE Trans. Indust. Electronics*., **44**, 579 (1997).

Depoy, J. A., "Analog Computer Simulation of Paper Drying A Workable Model," *Pulp & Paper Magazine of Canada*, **73**, 67 (1972).

Karlsson, M., "Results From On-Line Investigations of Paper Contact Drying Process," *Drying '80*, 322 (1984).

Karlsson, M., "Papermaking Science and Technology Book 9," Fapet Oy., 55 (2000).

Karlsson, M., Stenstrom, S. and Baggerud, E., "Dynamic Simulation of the Steam Supply System for a Multi-cylinder Dryer," *Nordic Pulp and Paper Res. J.*, **17**, 66 (2002).

Mori, Y., Shimizu, H., Takao, K., Ikari, T. and Nambu, T., "Development of A New Automatic Grade Change System for Paper Machine," Proceedings from Control Systems '2000, Victoria. B. C., Canada, 231 (2000).

Yeo, Y. K., Roh, H. D., Kim, I. W., Moon, I. and Chung, Y., "Optimal Operation of Utility Systems in Petrochemical Plants," *Korean J. Chem. Eng.*, **20**, 200 (2003).

Yoo, C. K., Lee, J. M. and Lee, I. B., "Nonlinear Model-based Dissolved Oxygen Control in a Biological Wastewater Treatment Process," *Korean J. Chem. Eng.*, **21**(1), 14 (2004).

Yu, Y. H. and Sosna, M. H., "Modeling for Industrial Heat Exchanger Type Steam Reformer," *Korean J. Chem. Eng.*, **18**(1), 127 (2001).