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.

1. 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 adequate amount of steam into 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 on the cylinder temperature and water content in the moving web, achievement of the optimal operation is far to be reached.

Utilization of a plant model in the operation is one of the most promising way to improve plant performance.[1] 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 attention of many researchers. About three decades ago an analog computer model for paper drying processes was proposed.[2] 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[3] to be used in the control operation during paper grade changes. In this model empirical relationships concerning evaporation rate and steam prediction were employed while heat transfer coefficients being kept constant. A state model for the paper drying process in a paperboard mill was presented.[4] 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 are provided.[5,6] Identification of heat transfer coefficients has been the key issue in the modeling of the paper drying process. Without any mean to detect 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 is 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.

2. Materials & Methods

2.1 Modeling of the Drying Process

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. 1 shows the drying cycle with single−tier configuration 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. 2 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 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 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

$$\frac{dT_1}{dt} = \frac{1}{L_D \rho_D C_D}\left\{h_s T_s - (h_s + h_{dw})T_1 + h_{dw}T_2\right\} \quad [1]$$

L_D : thickness of cylinder, m

ρ_D : density of cylinder, kg/㎥

C_D : specific heat of cylinder, ㎉/kg℃

h_s : heat transfer coefficient between the steam and the cylinder, ㎉/㎡sec℃
h_{dw} : heat transfer coefficient between the cylinder and the web, ㎉/㎡sec℃
T_s : steam temperature, ℃

From the balance around the web we have

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

D : bone-dry weight, kg/㎡
a_w : web moisture content
C_w : specific heat of web, ㎉/kg℃
h_{wc} : heat transfer coefficient between the web and the canvas, ㎉/㎡sec℃
m : evaporation rate, kg/㎡sec
ΔH_{ev} : heat of evaporation, ㎉/kg

where the specific heat of the web is given by

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

[3]
a_z : ash ratio

The evaporation rate m from the web can be expressed as

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

[4]
C_a : specific heat of dry bulb air, ㎉/kg℃
C_v : specific heat of vapor, ㎉/kg℃
x_s : air humidity at the web surface, kgH_2O/kg dry air
x : air humidity in the surrounding air, kgH_2O/kg dry air

h_e : heat transfer coefficient between the web and the air, ㎉/㎡sec℃

where the air moisture x_v and x are given by

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

[5]

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

[6]

P : Total pressure, bar

P_s : vapor partial pressure on the web surface, bar

P_w : vapor pressure in the surrounding air, bar

x_v : air moisture, kgH_2O/kg dry air

T_w : wet bulb temperature of air, ℃

T_d : dry bulb temperature of air, ℃

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

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

[7]

T_{we} : temperature of web, ℃

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

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

[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

$$T_r = \frac{T_{we}}{T_c} = \frac{T_{we}}{373.95} (T_{we} : {}^oC)$$

[10]

A correlation for the sorption isotherm[5] 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

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

[11]

R : gas constant, ㎉/kgmolK

φ : relative humidity of air

The relative humidity of the air can be written as

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

[12]

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

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

[13]

From the balance around the canvas we have

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

[14]

L_C : thickness of canvas, m

ρ_C : density of canvas, kg/㎥

C_c : specific heat of canvas, ㎉/kg℃

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 in 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

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

[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[5)]. But any explicit expression is not 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 was reported [3]. But, in most cases, values of heat transfer coefficients were assumed to be constant. Selection of the constant relied on the operational experience or was based on the experimental results for similar situations.

2.2 Analysis of the heat transfer coefficients.

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 of the form

$$h_{dw} = c_1 * \exp(c_2 * a_w) + c_3 * \exp(c_4 * a_w) \quad [19]$$

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

BW : basis weight, kg/㎡

V : reel speed, m/s

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} and h_e for the after-dryer section has of the form

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

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

[22]

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 1 shows values of the parameters for the plant being considered in the present study.

3. Results & Discussion

Several simulations were performed to validate the model developed in the present study. Three typical paper grades, the basis weights of which are 55 , 71 and 113 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 2 shows operating data used in the production of those papers as well as in the simulations.

Fig. 3 shows results of simulations for the main-dryer with h_e being kept constant for the paper with the basis weight of 55g/m^2. As mentioned before, constant heat transfer coefficients have been used in most of the drying models reported so far and the significant discrepancy between plant data and simulation results as can be seen in Fig. 3 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], [21] and [22] with the parameter values given in Table 1. Results of simulations for the main-dryer using the updated heat transfer coefficients are shown in Fig. 4 for the paper with the basis weight of 55 g/m^2. As can be seen in Fig. 4, the model tracks the measured operation data closely and we can validate the effectiveness of the present model.

For the after-dryer, no appreciable modeling results were reported and we applied variable heat transfer coefficients given by [21] and [22] with the parameter values given in Table 1. Results of simulations are shown in Fig. 5 for the paper with the basis weight of 55g/m^2. 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. 6, 7, 8 and 9 show the profile of the moisture content for the paper with the basis weight of $71g/m^2$ and $113g/m^2$. The web temperature shown in Fig. 6, 7, 8 and 9 are 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 3. We can see that the proposed model predicts the moisture content at each dryer section with sufficient accuracy.

4. Conclusions

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.

Literature Cited

1. Yeo, Y. K., Roh, H. D., Kim, I. W., Moon, I. and Chung, Y., Korean J. Chem. Eng., 20(2):200 (2003).
2. Depoy, J. A,. Pulp & Paper Magazine of Canada., 73: 67(1972).
3. Mori, Y., Shimizu, H., Takao, K., Ikari, T. and Nambu, T., 2000 Proceedings from Control Systems, Victoria.B.C, Canada, p.231.
4. Berrada, M., Tarasiewicz, S., Elkadiri, M. E. and Radziszewski, P. H., IEEE Trans. Indust. Electronics., 44(4):579(1997).
5. Karlsson, M., Papermaking Science and Technology., Vol.9, p.54, Tappi press, Helsinki, (2000).
6. Karlsson, M. Drying 80., 322(1984).

Table 1. Parameters for heat transfer relations.

Parameter	Main-dryer	After-dryer
c_1	0.1394	2.534
c_2	1.354	−0.9811
c_3	−0.0916	0.5156
c_4	−8.32	0.14
k_1	0.0032	0.0273
k_2	1.2733	0.525
k_3	−0.002	−0.023
k_4	−8.29	−
n	0.52	0.63

Table 2. Data for simulations.

Description	Basis weight [g/m^2]		
	55	71	113
Reel speed [m/min]	1209	1225	989
Ash content [%]	12.6	15.7	19
Amount of sizing [g]	2.5	2.6	3.5
Sizing consistency [%]	12	12.5	16
Moisture content at the main-dryer outlet [%]	3.5	3.7	6.5
Moisture content at the after-dryer outlet [%]	2.6	2.9	3.3
Steam to the 1st group [kg/cm^2]	−0.45	−0.29	−0.37
Steam to the 2nd group [kg/cm^2]	0.11	0.38	0.82
Steam to the 3rd group [kg/cm^2]	0.13	0.46	0.96
Steam to the 4th group [kg/cm^2]	0.20	0.71	1.38
Steam to the 5th group [kg/cm^2]	0.28	1.02	1.82
Steam to the 6th group [kg/cm^2]	0.33	1.02	1.81
Steam to the 7th group [kg/cm^2]	0.19	0.44	0.60
Steam to the 8th group [kg/cm^2]	0.39	0.87	1.02
Steam to the 9th group [kg/cm^2]	0.39	0.87	1.06

Table 3. Moisture content at the outlet of main- and after-dryer.

Basis weight [g/m^2]	Main-dryer		After-dryer	
	Operation [%]	Simulation [%]	Operation [%]	Simulation [%]
55	3.5	3.63	2.6	2.62
71	3.7	3.42	2.9	2.82
113	6.5	6.45	3.3	3.37

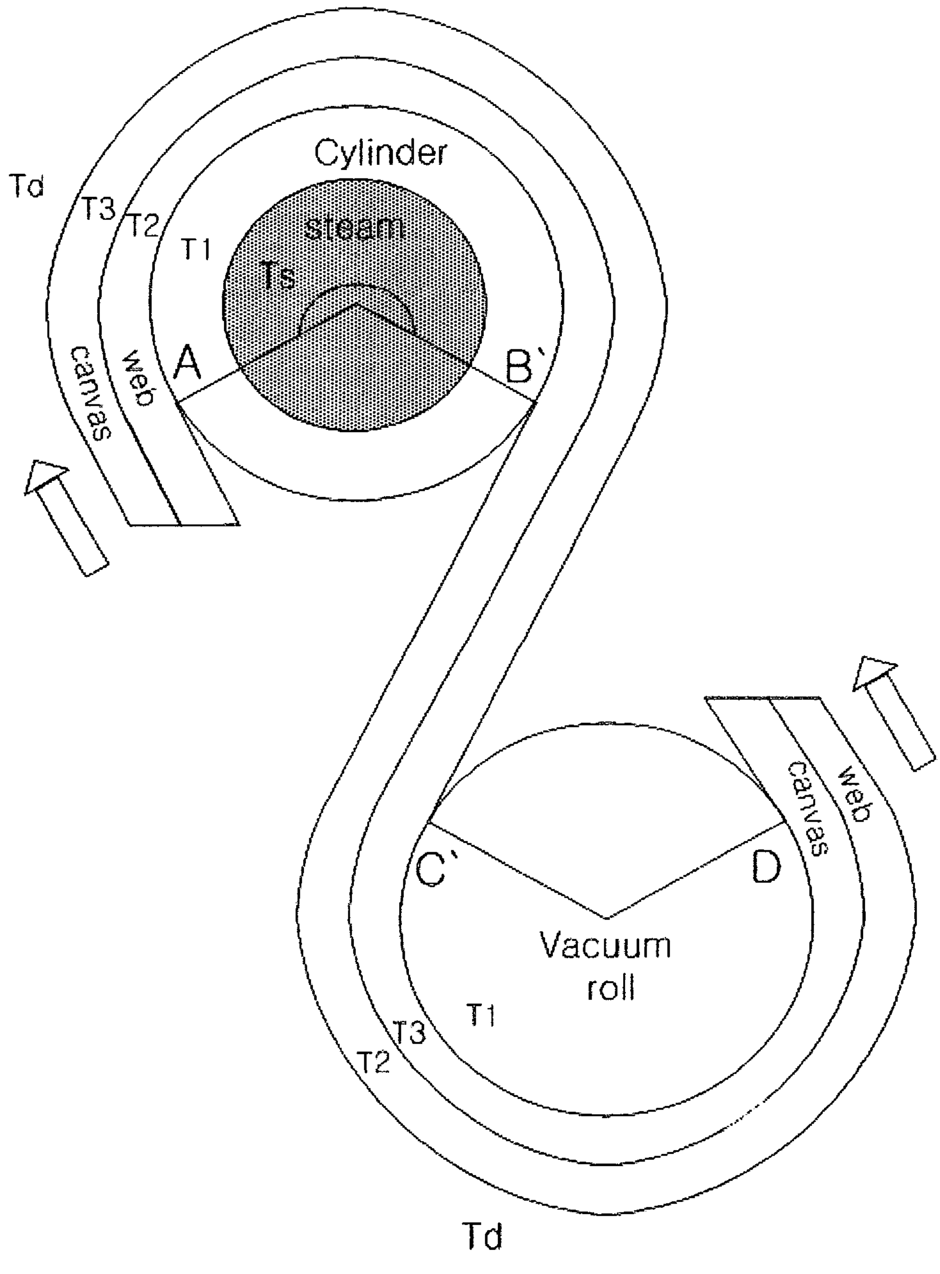

Figure 1. Drying cycle with single – tier configuration.

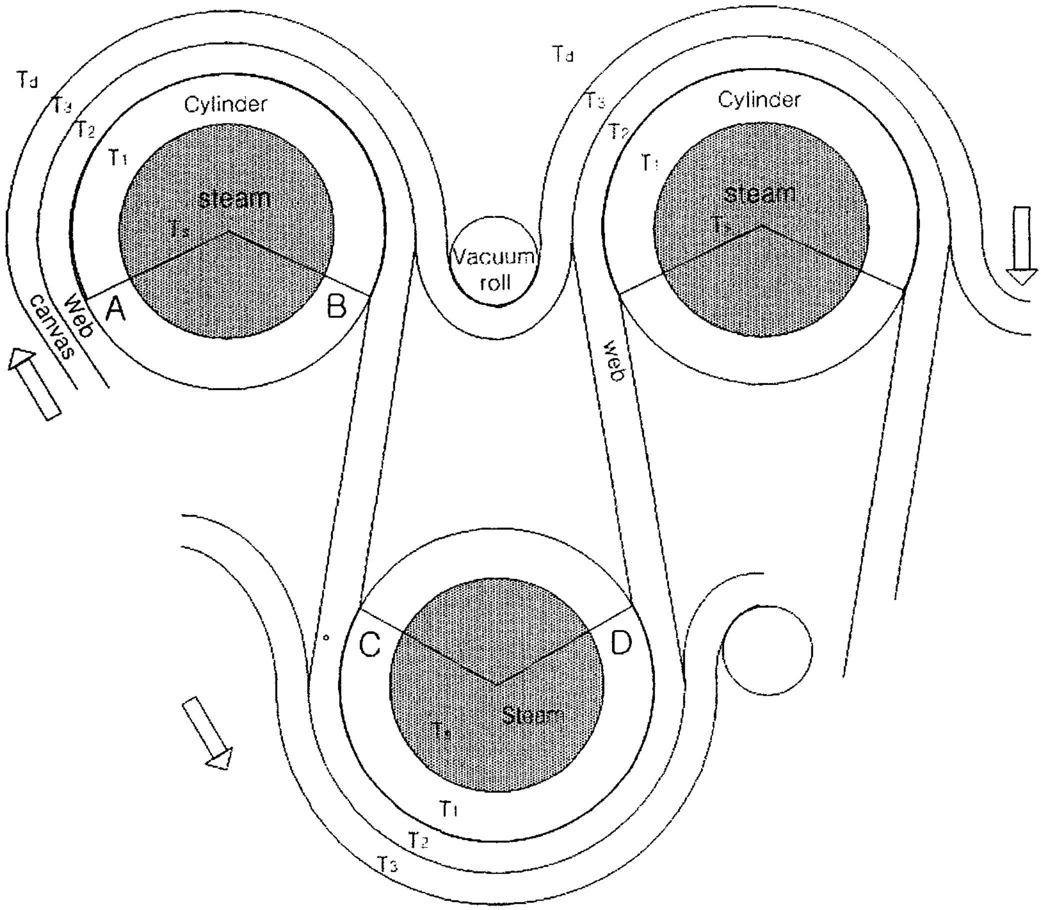

Figure 2. Drying cycle with double−felted configuration.

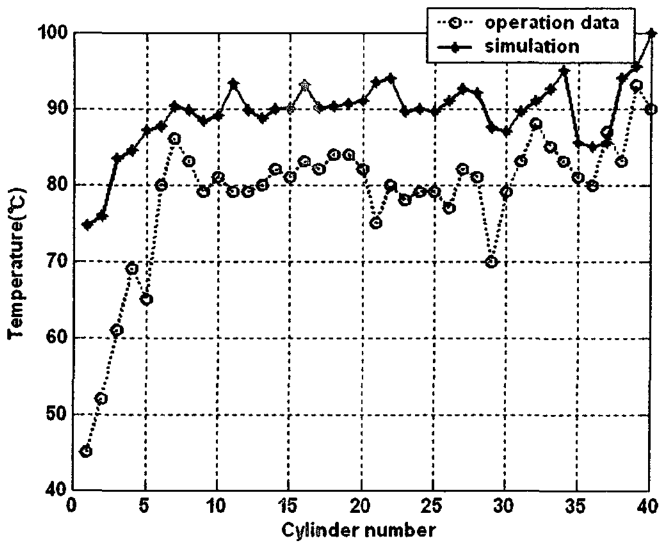

Figure 3. Main−dryer temperature profile : constant heat transfer coefficients. [basis weight : 55g/m^2]

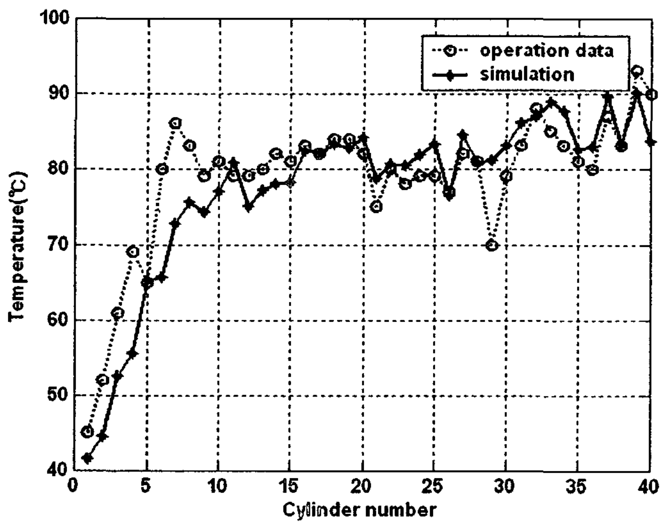

Figure 4. Main−dryer temperature profile : variable heat transfer coefficients. [basis weight : 55g/m^2]

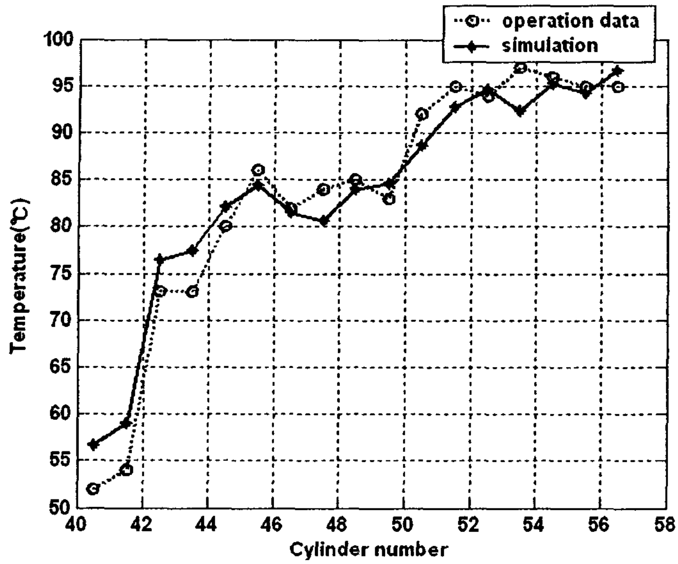

Figure 5. After−dryer temperature profile : variable heat transfer coefficients. [basis weight : 55g/m^2]

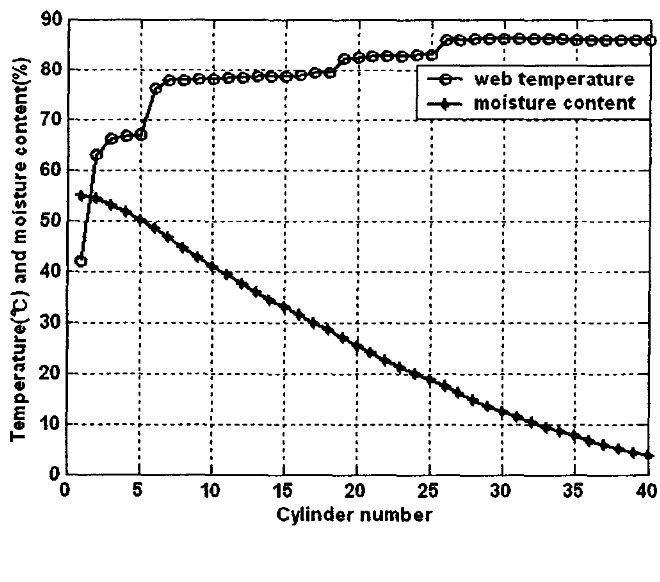

Figure 6. Main−dryer moisture content : variable heat transfer coefficients. [basis weight : 71g/m^2]

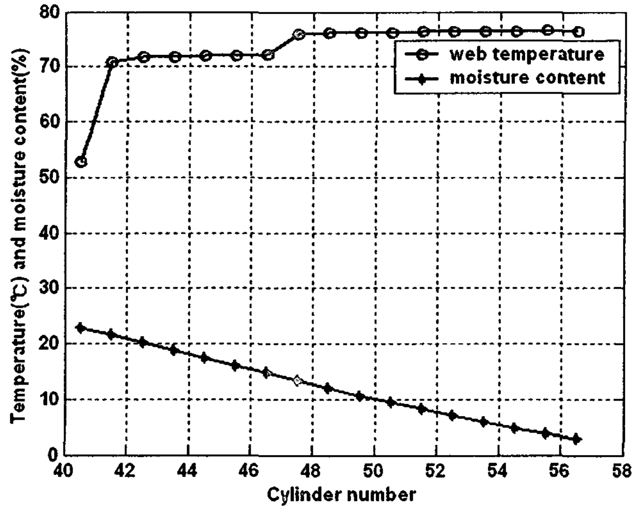

Figure 7. After−dryer moisture content : variable heat transfer coefficients.

[basis weight : 71g/m^2]

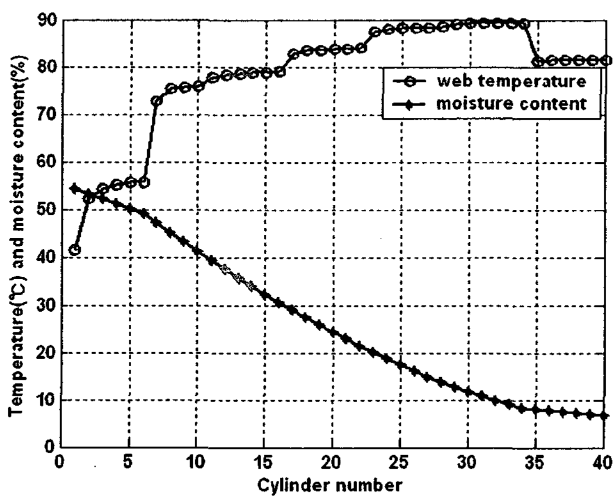

Figure 8. Main−dryer moisture content : variable heat transfer coefficients.

[basis weight : 113g/m^2]

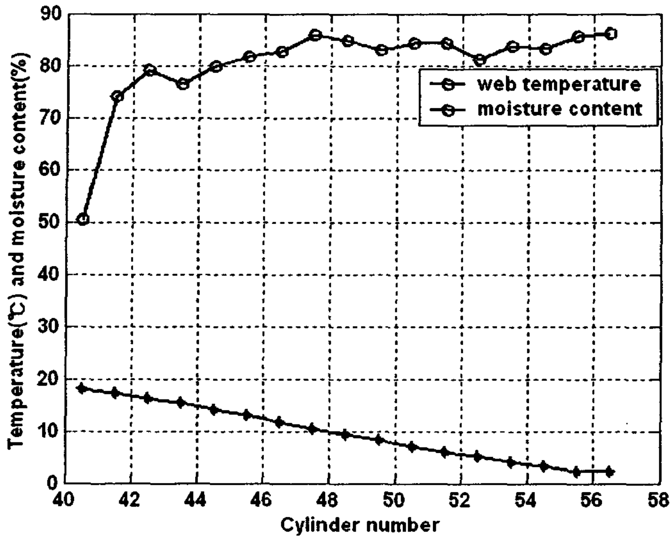

Figure 9. After−dryer moisture content : variable heat transfer coefficients.
[basis weight : 113g/m^2]