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Modeling and Simulation of Wet-end White Water System in the Paper Mill

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Abstract−A dynamic model representing the wet-end of a paper mill is developed to characterize its dynamic behavior. The model is based on the mass balance relationships written for the simplified wet-end white water network. The dynamic response of the wet-end is influenced both by the white water volume and by the level of wire retention. Effects of key manipulated variables such as the thick stock flow rate, the ash flow rate and the retention aid rate on the major controlled variables are analyzed by numerical simulations. It can be said that the consistency of the model with plant data seems to be reasonably good and can be used as a tool for plant analysis and control.

Key words: Bone-dry Weight, Consistency, Dynamic Model, Paper Mill, Retention, Simulation, Wet-end

INTRODUCTION

The increased stringent environmental demands on paper production have led to the use of more closed wet-end systems with considerable material recirculation. The complexity of the wet-end system of a paper mill is not readily apparent. The formation of a sheet of paper is a continuous process in which cellulose fibers, fines, fillers and additives form a network that is then pressed and dried. A three-dimensional network is formed by the mechanical entanglement of the fibers and by the chemical interactions between the different pulp fractions. It is possible to operate a paper machine successfully without a detailed understanding of how the changes in one part of the system will affect the other parts of the system. But, when operational troubles arise, it is necessary to interpret plant data correctly and to cross check the normal operating conditions of the plant. It is helpful to have current information on a particular system at hand when required, rather than to rely on spot-sampled data with relatively low reliability. A dynamic model can be a powerful tool to provide reliable data for a particular section being considered. Apart from the process control and trouble-shooting for the wet-end section, the dynamic model can be an essential tool in the design of new systems and in the modification of existing systems [Yeo et al., 2003; Kim and Koo, 2003; Lee and Ko, 2002], as well as in the analysis of process variables and in the identification of the effect of various additives on the dynamic behavior of the system.

Simple white water material balances for the wet-end system were proposed to compute equilibrium concentrations of solid components [Mardon et al., 1972]. A steady-state model of this kind can be used to check the abnormality of the present operational status. With rapid development and application of various computer operation-aid systems, the operation of the plant is monitored and controlled on-line and the steady-state model can find its use only in very restricted area. Investigations on dynamics of the short circulation system with constant retentions were reported [Bo, 1990]. During the operation, retention changes due to machine speed changes, basis weight changes and retention aid changes. Retention changes have great effect on basis weight and ash percentage controls. However, there is no physically based dynamic model to predict the behavior of key controlled variables for given operating conditions. A dynamic model is especially useful for investigating the dynamic behavior of the wet-end system during the grade change. Use of a simple plant-wide dynamic model in the transition control during a grade change was proposed [Murphy and Chen, 1999; Skoglund and Brundin, 2000]. Application of model predictive control schemes based on the transfer function dynamic models was also reported [Hauge and Telemark, 2001].

The objective of the present work is to develop a simple dynamic model for a wet-end section to analyze the transient behavior of the white water network. There are many benefits of simplified dynamic models such as less computational time, easier analysis and interpretation and convenient controller design. The model gives the bone-dry weight of the paper and dynamics of the retention for specific operating conditions.

WET-END MODELING

1. Simple Short Circulation

Fig. 1 shows a simplified wet-end system of a paper plant. In Fig. 1, the thick stock rate Q_0, the ash flow rate Q_f, the ash fraction of the thick stock X_{0a} and the flow rate of the retention aid Q_p are as-

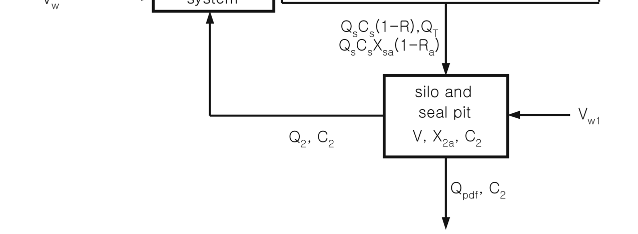

Fig. 1. Schematics of wet-end system.

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sumed to be known, i.e., they are manipulated variables. These variables become input data for the model to be developed.

First we define a parameter p1 as

$$p1=k\cdot P_w\cdot S_w\cdot J_r\cdot C_F\cdot 1000 \tag{1}$$

where S_w and P_w are the width of the slice and the pond, respectively, and C_F is the headbox slice factor which is dependent upon the configuration of the outlet device of the headbox. The product $P_w\cdot S_w\cdot C_F$ gives the area of the headbox outlet section. J_r represents the jet/wire ratio, which is defined as the ratio of the flow rate from the headbox to the wire speed. In normal operations, J_r is slightly greater than 1. Due to the draw in the drying section, the paper web moves faster in the reel section than in the wire. The factor k represents the difference in the speed between the wire section and the reel part. In most operations the speed in the wire section is 97% of the speed in the reel section. This means that we can set the value of k as 0.97 in most cases. The flow rate from the headbox Q_s is given by

$$Q_s=p1\cdot V_r \tag{2}$$

where V_r is the reel speed. Q_s is the jet flow rate form the slice taking into account of the effect of Vena contractor. The flow rate to the press is then expressed as

$$Q_d=\frac{p1\cdot V_r\cdot C_s\cdot R}{C_d} \tag{3}$$

where R is the retention ratio, C_s is the consistency in the headbox and C_d is the consistency of the stream to the press. C_d lies in the range of 18-22% and is set to 20% in the simulations. The product $p1\cdot V_r\cdot C_s$ is the amount of the mass from the headbox. From the simple material balance around the wire and the tray, the flow rate Q_T of the stream to the silo and the seal pit is given by

$$Q_T=Q_s-Q_d=p1\cdot V_r-\frac{p1\cdot V_r\cdot C_s\cdot R}{C_d} \tag{4}$$

The flow rate of the stream to save-all Q_{pdf} can be obtained from the material balance around the wire, the silo and the seal pit and can be expressed as

$$Q_{pdf}=Q_s-Q_d-Q_2 \tag{5}$$

Q_2 is the flow rate of the internal circulation stream and is given by

$$Q_2=Q_s-Q_0-Q_f-Q_p-V_w \tag{6}$$

where V_w is the amount of dilution water. Perfect mixing in all the components (Fig. 1) with significant volume is assumed in this simplified model.

2. Silo and Stock Approach Section

Dynamics of the solid and ash contents in the silo and the seal pit can be expressed as

$$V\frac{dC_2}{dt}=(1-R)Q_sC_s-Q_2C_2+Q_{pdf}C_2 \tag{7}$$

$$V\frac{dX_{2a}}{dt}=(1-R_a)Q_sC_sX_{sa}-Q_2C_2X_{2a}+Q_{pdf}C_2X_{2a} \tag{8}$$

where C_2 is the silo consistency, X_{2a} is the ash fraction in the silo and R_a is the ash retention. V denotes the total volume of the silo and the sealpit. Similarly, the dynamics in the stock approach section are given by

$$V_s\frac{dC_s}{dt}=Q_0C_0+Q_2C_2+Q_fC_f-Q_sC_s \tag{9}$$

$$V_s\frac{dC_sX_{sa}}{dt}=Q_0C_0X_{0a}+Q_2C_2X_{2a}+Q_fC_f-Q_sC_sX_{sa} \tag{10}$$

In this study, the stock approach section includes screens and cleaners as well as deculator. Because of the complexity of the configuration of cleaner sections and screens and of the considerable volume of the deculator, we assumed a tank with volume V_s to represent the stock approach section. We assumed that the flow from the tank becomes the outlet flow from the headbox. V_s includes the volume of the deculator, the volume of the 1st and 2nd cleaner lines and the volume of 1st and 2nd screen lines.

3. Retention and BD

Retention is affected by many factors such as the amount and types of retention aids, thick stock rates, types of pulp, SRE (specific refinery energy), fiber fine fraction in the thick stock, the wire speed, filler flow rates, temperature of the white water, PH, ash contents in the white water and the thick stock, and the wire mesh [Neimo, 2000]. In this work we are considering only the "short-term dynamics" during grade changes rather than the "long-term dynamics." Then we can assume that retentions exhibit the first-order dynamics and can represent the behavior of R and Ra as

$$\frac{dR}{dt}=\frac{k1}{\tau}Q_p-\frac{R}{\tau} \tag{11}$$

$$\frac{dR_a}{dt}=\frac{k2}{\tau}Q_p-\frac{R_a}{\tau} \tag{12}$$

where τ is the retention time constant, k1 is the retention constant and k2 is the ash retention constant. k2 was assumed to be 1/3 of k1. k1 can be obtained from the steady-state retention and the amount of the retention aid. τ depends on the specific paper machine being used.

The bone dry weight BD and the ash bone dry ashBD are given by

$$BD=Q_s\cdot C_s\cdot R\cdot(C_w/p_w)\cdot w_r\cdot 1000/(V_r\cdot r_w) \tag{13}$$

$$ashBD=Q_s\cdot C_s\cdot X_{sa}\cdot R_a\cdot(c_w/p_w)\cdot w_r\cdot 1000/(V_r\cdot r_w) \tag{14}$$

where c_w and p_w are widths of the couch and the pond, respectively, and r_w is the reel width. w_r is the diminishment ratio of BD or ash BD which can occur unexpectedly while the paper web passes the press and dryer section.

The assumptions employed in the present study can be summarized as the following:

i) k1 is defined as $k1=R_{a,i}/Q_{p,I}$, i.e., k1 is defined as the initial retention divided by the reteino aid rate.

ii) The retention shows 1^{st}-order dynamics to the change of retention aid rates.

iii) Perfect mixing is achieved in the silo and the stock approach section. This assumption is justified considering the fact that consistencies at the 1^{st} cleaner accept, deculator outlet, 1^{st} screen accept, and headbox outlet do not show large discrepancy.

iv) Thick stock ash fraction is constant.

Table 1. Initial values for state variables

State variables	C_s (kg/l)	X_{sa} (-)	C_2 (kg/l)	X_{2a} (-)	R (%)	R_a (%)
Simulation 1	0.00772	0.3	0.0019	0.52	74	46
Simulation 2	0.009	0.3	0.0022	0.45	75	51

Table 2. Constants and parameters

Description	Simulation 1	Simulation 2
C_0 (kg/L) or (%/100)	0.0328	0.0328
X_{0a} (-)	0.076	0.087
C_f (kg/L) or (%/100)	0.46	0.47
C_d (kg/L) or (%/100)	0.2	0.2
V (Liter)	105,000	105,000
V_s (Liter)	50,000	50,000
V_w (Liter)	1,000	1,000
V_{w1} (Liter)	2,000	2,000
k1 (min/L)	0.0158	0.0142
τ (min)	800	800
P_w (Meter)	5.65	5.65
R_w (Meter)	4.06	4.06
C_w (Meter)	5.17	5.17
S_w (Meter)	0.01021	0.01021
C_F (-)	0.92	0.92
J_r (-)	1.04	1.05
W_r (-)	0.85	0.85

NUMERICAL SIMULATIONS

In the modeling equations, C_s, X_{sa}, C_2, X_{2a}, R and R_a can be considered as state variables. Suitable initial values for these variables should be assigned for the computations to be possible. Usually steady-state values for these variables are used as initial values. Table 1 shows initial values for the state variables used in the present work. Constants and parameters to be fixed for the computation are given in Table 2. Matlab (v. 6.5) was used as the simulation tool.

Two data sets obtained from the grade change operations were used to validate the simplified dynamic model. The first data set, being compared with the results of the simulation 1, was obtained during the change of the bone-dry weight (BD) from 54 g/m^2 to 67 g/m^2 (or from 60 g/m^2 to 70.8 g/m^2 in the basis weight (BW)). The second data set for the change of the BD from 66 g/m^2 to 56 g/m^2 (or from 70.6 g/m^2 to 59.5 g/m^2 in BW) was compared with the results of the simulation 2.

In the model, rates of the thick stock flow, the retention aid and the filler inlet and the reel speed serve as input variables. Figs. 2 and 3 show changes of input variables used both in the actual plant operation and in simulation 1. The same input variables were fed into the plant as well as the model. Results of the simulation 1 are shown in Figs. 4, 5 and 6. Two key output variables (BD and ash BD) and four major state variables (consistencies in the silo and the headbox, the slurry rate and the retention ratio) were computed. Even with the up-to-date DCS technology, not all the variables are measured in the operation. In the plant being considered, BD and ash BD were detected online. We can see that the simplified model

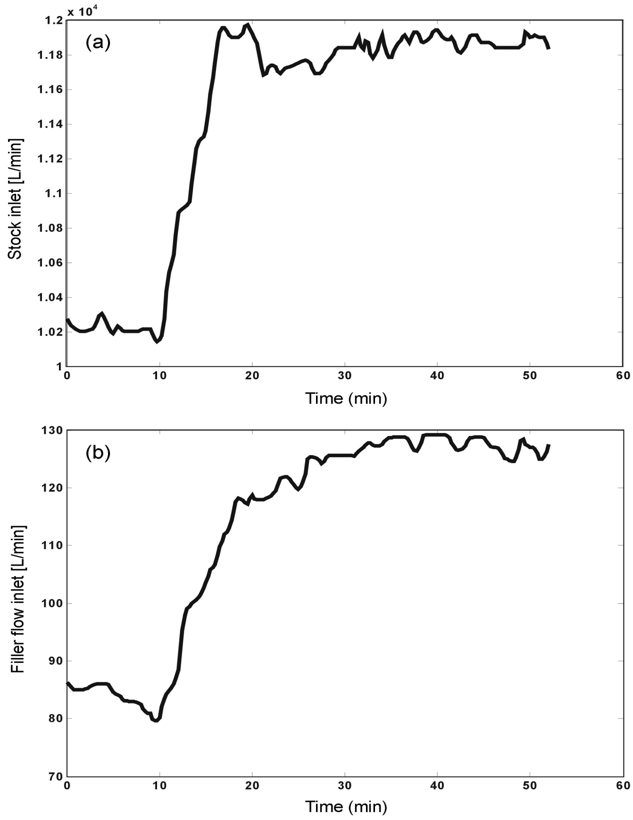

Fig. 2. Input flow rates of stock (a) and filler (b) (Simulation 1).

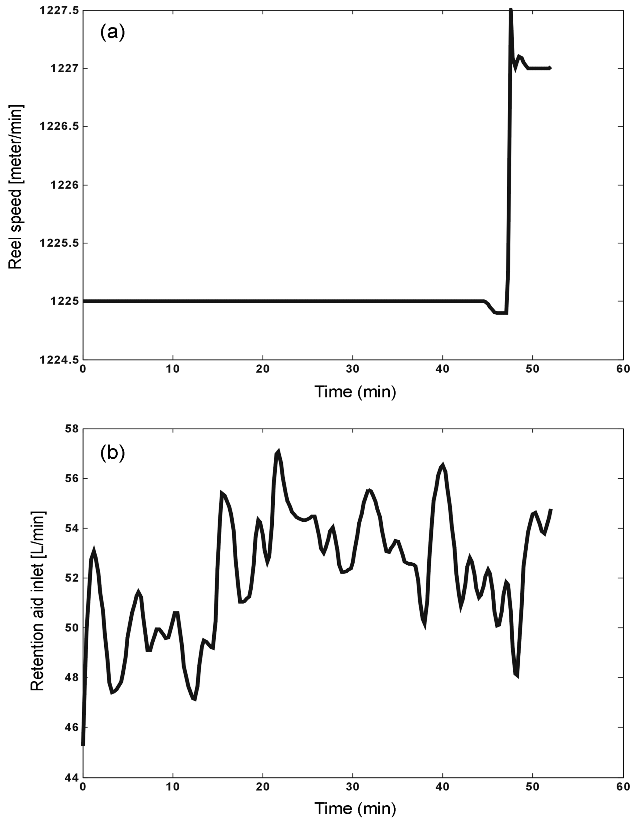

Fig. 3. Reel speed (a) and flow rates of the retention aid (b) (Simulation 1).

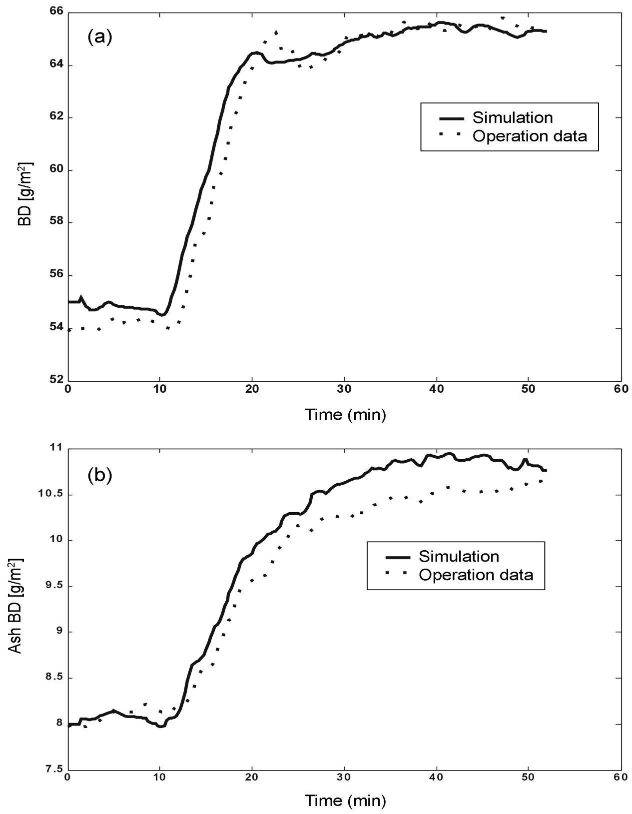

Fig. 4. Dynamics of bone-dry weight (a) and ash bone-dry weight (b) (Simulation 1).

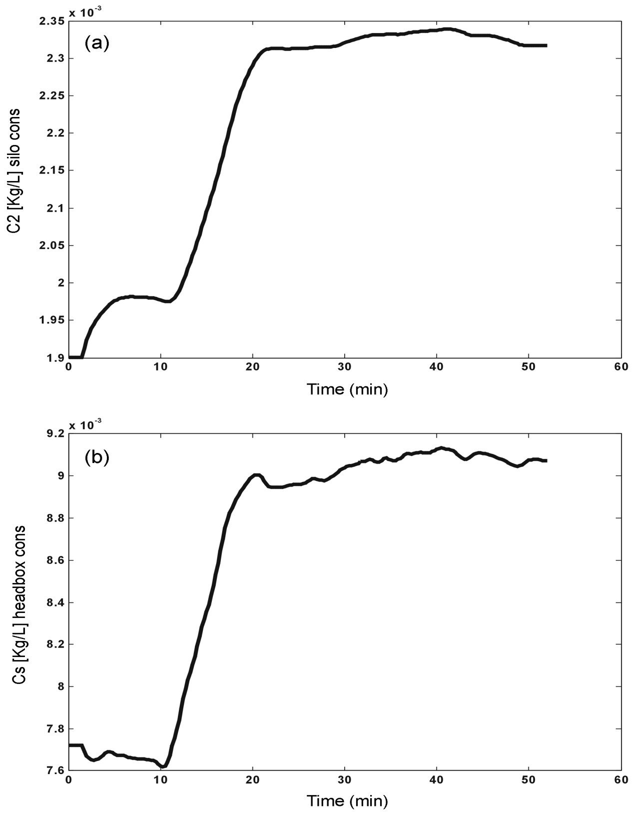

Fig. 5. Dynamics of silo consistency (a) and headbox consistency (b) (Simulation 1).

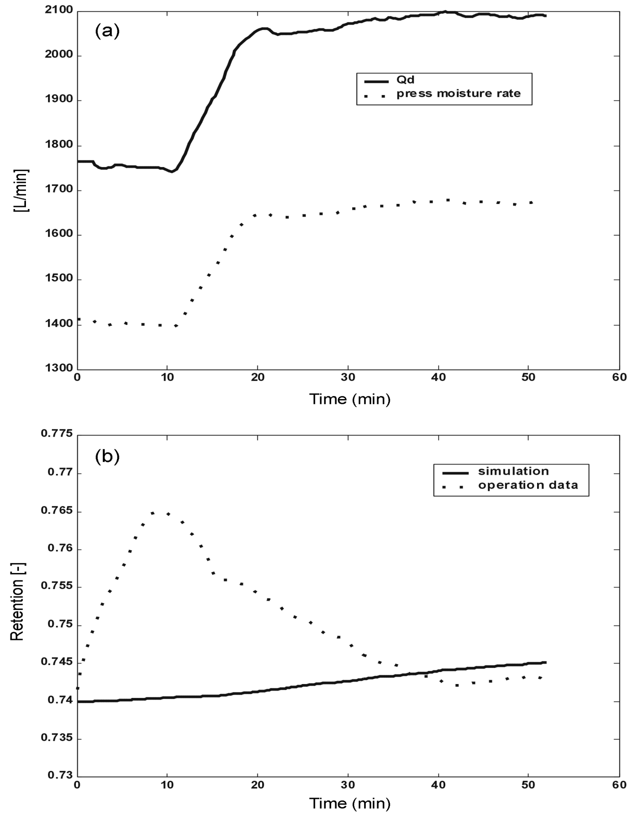

Fig. 6. Dynamics of slurry and moisture rates to the press (a) and retention ratio (b) (Simulation 1).

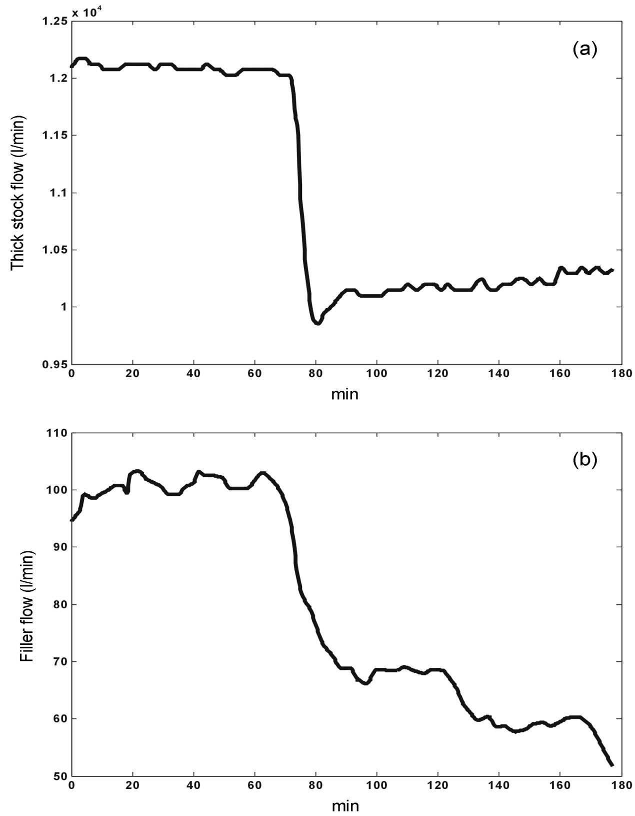

Fig. 7. Input flow rates of stock (a) and filler (b) (Simulation 2).

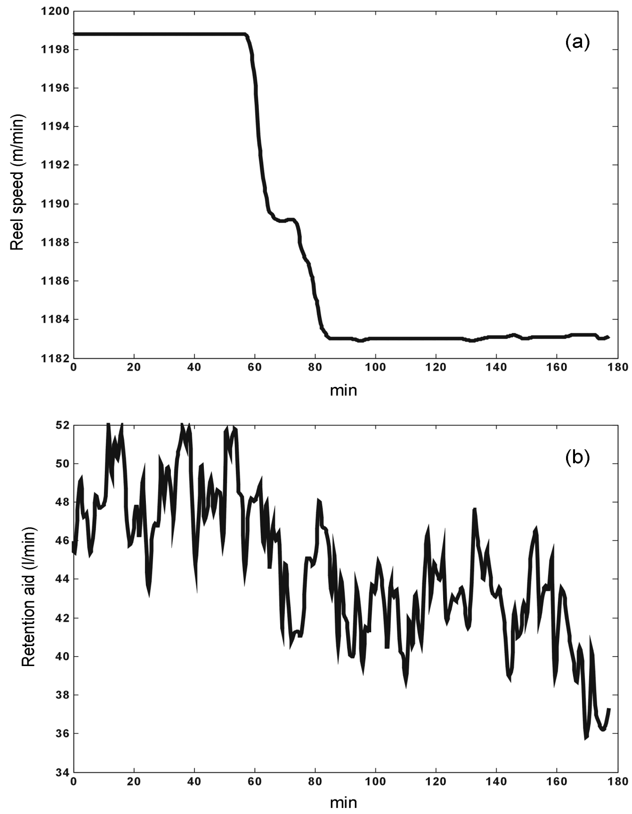

Fig. 8. Reel speed (a) and flow rates of the retention aid (b) (Simulation 2).

developed in the present study exhibited satisfactory tracking performance for the plant. The computed consistencies in the silo and the headbox shown in Fig. 5 display dynamic characteristics as expected. The smooth behavior of the silo consistency is not surprising considering the assumption of perfect mixing in the silo. Fig. 6 shows the slurry rate and the retention ratio obtained from simulation 1. The retention ratio is another variable being detected online. The cause of the big discrepancy in the beginning is not clarified yet. But, without knowledge of the details of the detecting mechanism of the retention ratio, we can only say that the assumption of perfect mixing in the silo might cause the discrepancy. The magnitude of the discrepancy is confined within the range of 3% difference, which does not have any significant effect on BD and ash BD.

Figs. 7 and 8 show changes of input variables used both in the actual plant operation and in simulation 2. Results of the simulation 2 are shown in Figs. 9, 10 and 11. As in simulation 1, two key output variables (BD and ash BD) and four major state variables (consistencies in the silo and the headbox, the slurry rate and the retention ratio) were computed. We can see that the simplified model tracks the plant well as in simulation 1. The consistencies in the silo and the headbox obtained in simulation 2 are shown in Fig. 10. Fig. 11 shows the slurry rate and the retention ratio obtained from simulation 2. Contrary to simulation 1, the simplified model exhibits the correct trend in the change of the retention ratio.

In actual plant operations, the maximum permissible limit of errors in BD is ±1 g/m^2 and variances in ash BD matter little when the basis weight and the moisture content lie within some permissible range. From the results of simulations we can see that BD stays

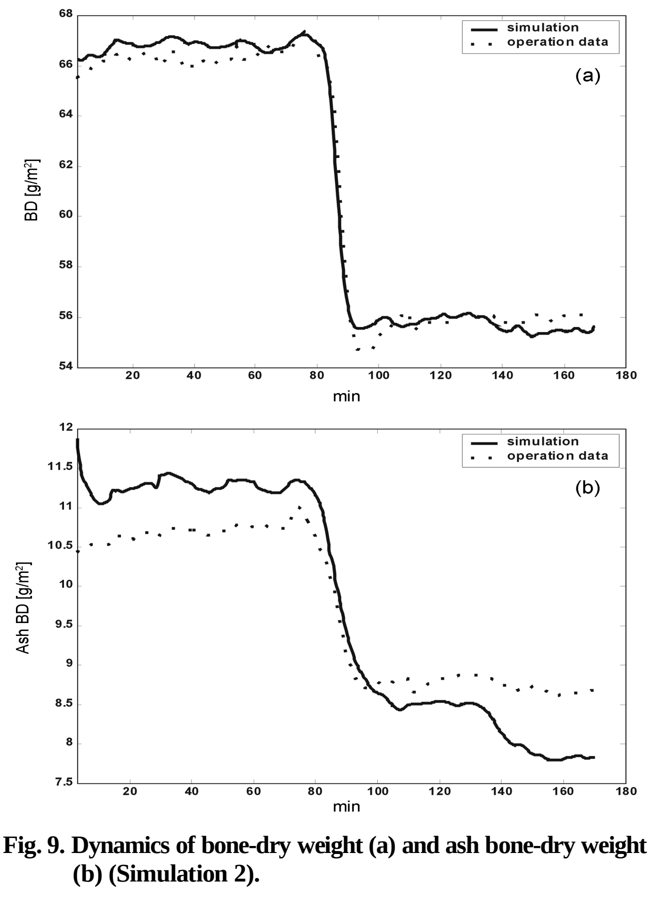

Fig. 9. Dynamics of bone-dry weight (a) and ash bone-dry weight (b) (Simulation 2).

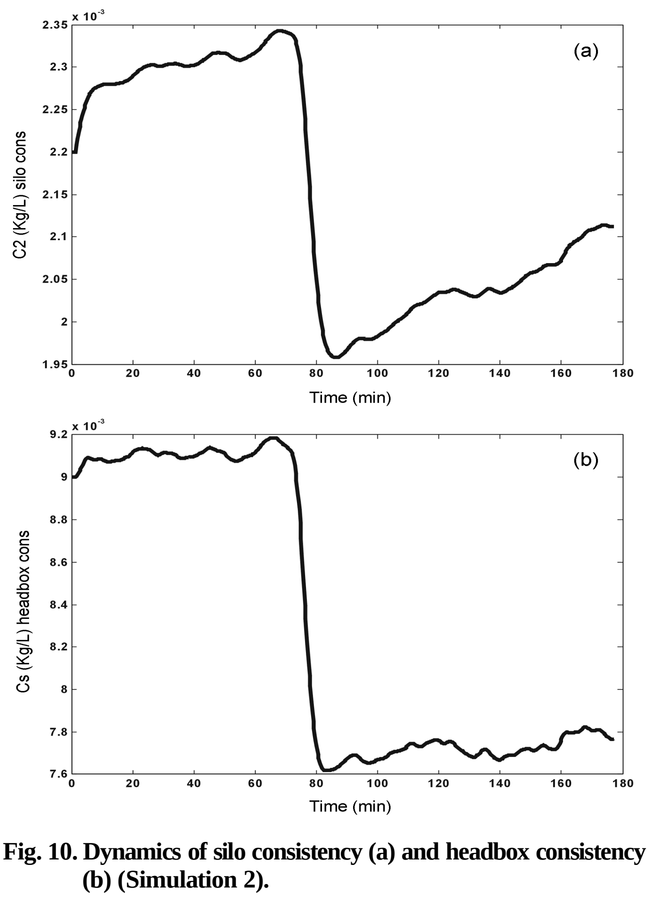

Fig. 10. Dynamics of silo consistency (a) and headbox consistency (b) (Simulation 2).

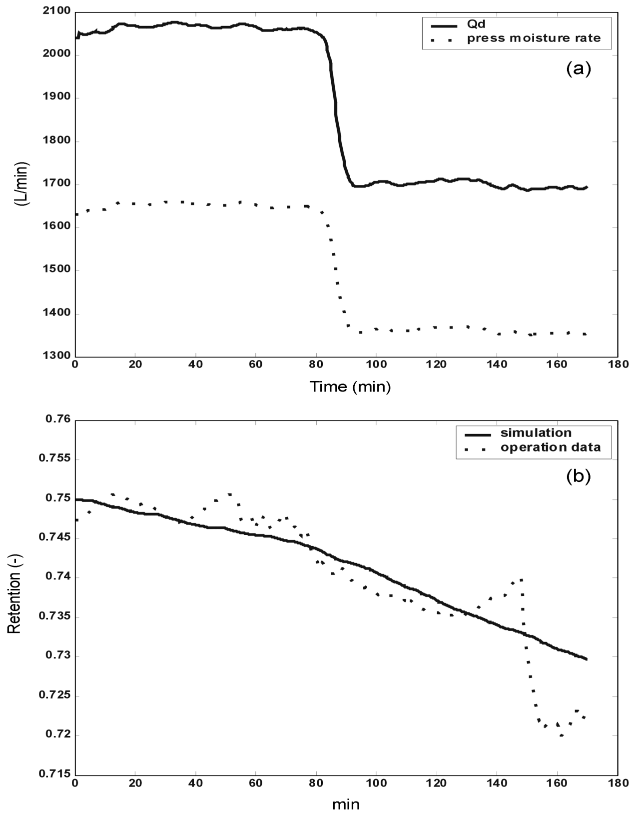

Fig. 11. Dynamics of slurry and moisture rates to the press (a) and retention ratio (b) (Simulation 2).

within the permissible error range, which demonstrates that the present model can be effectively used in the grade change control operation.

CONCLUSIONS

In the present study a simplified dynamic model for the wet-end in a paper mill was proposed. There are many benefits of simplified dynamic models such as less computational time, easier analysis and interpretation and convenient controller design. Dynamics of major state variables including consistencies in the silo and the headbox as well as the retention ratio could be represented in terms of simple differential equations. Two input data sets were employed both in the actual operation and numerical simulations. A comparison between the plant operation data and the results of numerical simulations shows the effectiveness of the simplified dynamic model proposed in the present work.

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NOMENCLATURE

C_0 : consistency in the thick stock [kg/L] or [%/100]
C_2 : consistency in the silo [Kg/L] or [%/100]
C_f : consistency in the filler flow [kg/L] or [%/100]
C_F : headbox slice factor [-]
C_s : consistency in the headbox [Kg/L] or [%/100]
C_w : width of the couch [m]
k : speed factor [-]
k1 : retention constant [min/L]
k2 : ash retention constant [min/L]
Q_0 : thick stock flow rate [L/min]
Q_2 : internal recirculation flow rate [L/min]
Q_d : flow rate to the press [L/min]
Q_f : ash flow rate [L/min]
Q_p : flow rate of the retention aid [L/min]
$Q_{p,i}$: initial retention aid flow [L/min]
Q_{pdf} : flow rate to saveall [L/min]
Q_s : outlet flow rate from the headbox [L/min]
Q_T : flow rate in the tray [L/min]
R : retention ratio
R_a : ash retention ratio
$R_{a,i}$: initial retention aid flow [L/min]
P_w : pond width [m]
R_w : reel width [m]
S_w : the width of the slice [m]
V : silo volume [L^3]
V_r : reel speed [m]
V_s : stock approach volume [L^3]
V_w : the amount of dilution water [L/min]
V_{w1} : clean water rate to the silo [L/min]
W_r : diminishment ratio [-]
X_{0a} : ash fraction in the thick stock [-]
X_{2a} : ash fraction in the silo [-]
X_{sa} : ash fraction in the headbox [-]

Greek Letter

τ : retention time constant [min]

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