Dynamic Simulation of Retention and Formation Processes

of a Pilot Paper Machine

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ABSTRACT

In an effort to develop control strategies for the wet-end of paper machines, dynamic models for retention and formation processes have been developed. The retention process, including headbox total and filler consistencies, white water total and filler consistencies, the basis weight and the ash content of paper, can be modeled from first-principles (mass balances). To include the effect of wet-end chemistry variables, first-pass retention was included as a parameter dependent on operating conditions. In addition, dynamics of formation was simulated by developing an empirical model of formation and coupling with the dynamic models for the retention process. A series of experiments were performed using a pilot paper machine. The experimental results and the model predictions showed relatively good agreement.

Keywords : dynamic simulation, modeling, retention, formation

1. Introduction

Wet-end control of papermaking has been a major issue in recent years due to its profound effect on paper quality and process efficiency. From the perspective of paper quality control, two important properties are: the machine direction (MD) variability and the uniformity of spatial distribution of solid materials in paper. The former, related to the retention process, includes the headbox pulp and filler consistencies, the white water pulp and filler consistencies, the basis weight and the ash content of paper; and the latter, related to the formation process, includes fiber flocculation in a headbox and formation of paper.

What makes it difficult to control is the complexity of the wet-end process. More than 90 % of the white water is reused, and the effect of colloid chemistry at the wet-end on retention of solids and formation of

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paper has only been partially characterized yet. Hence, black box approaches have been mostly used to model and control the dynamics of the retention process (1-5). Using a first-principles modeling approach, the steady state and dynamic simulation of the wet-end of paper machines has already been established for decades (6-9). The main difficulty is to implement the effect of wet end chemistry on the retention process. Moreover, the dynamic modeling of formation has not been attempted yet. In a previous study (10), it was shown that the effect of wet end chemistry can be included by using first-pass retention as a variable dependent on certain process factors and simulation results of the dynamics of paper ash content were compared with experimental data.

The objective of the present study was to model and to simulate the dynamics of the retention process (headbox and white water consistencies, basis weight and paper ash content) together with formation as a function of process variables.

2. Modeling

2.1 Process description

The experiments were performed on the pilot paper machine at the Centre Spécialiséen Pâtes et Papiers (CSPP), CEGEP de Trois-Riviéres. The pilot paper machine is illustrated in Fig. 1. This is a Fourdrinier paper machine, 76 cm wide, operating typically at a velocity of 40 m/min (with maximum speed of 90 m/min). Pulp from a high consistency pulper is refined using a conical refiner, stored in stock chests, and sent to a machine chest. Thick stock from the machine chest is diluted with the white water from a wire pit, and then delivered to the centrifugal cleaners and to a pressure screen to remove contaminants. The headbox is of the open type. Drainage is achieved by 18 table rolls, 4 vacuum boxes and a couch roll. The drained water from the wire section is collected at the wire pit to be reused to dilute thick stock. The wet web is pressed with 2 nips, dried, and calendered. On-line sensors (ABB) are located after the calender to measure basis weight, ash content, formation, moisture content, caliper, brightness, and opacity of paper. Kajaani Rmi sensors are used to measure headbox total and filler consistencies and white water total and filler consistencies: the white water consistency sensor is installed at the white water tray.

2.2 Dynamic modeling

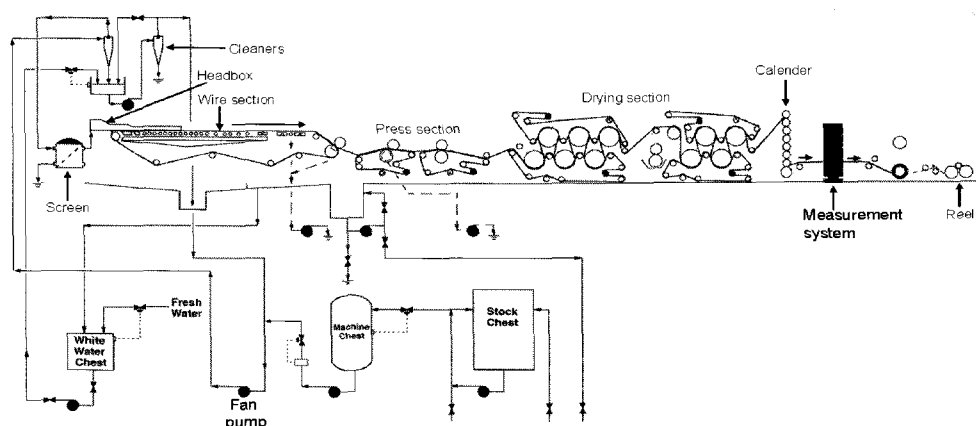The paper machine representation was simplified as

Fig. 1. Pilot paper machine at the Centre Spécialisé en Pâtes et Papiers (CSPP), CEGEP de Trois-Riviéres.

shown in Fig. 2, to highlight the short circulation loop of white water. The couch pit, savealls, machine chests, a screen, cleaners, etc. were omitted. The model is a three-fractional model, which handles fiber, fines and filler consistency. In the headbox and the white water tank, the mixing is assumed to be ideal, i.e. there is the same consistency everywhere in the volume.

Thick stock was assumed to consist of fiber, fines and filler. The dynamics of the headbox consistencies $C_{2,i}$ (i = fines, filler and fiber, g/L) can be obtained from the mass balances around the headbox:

$$\frac{dC_{2,i}}{dt} = \frac{1}{V_{hb}}(F_1 C_{1,i} + F_7 C_{7,i} + F_5 C_{5,i}) - \frac{F_2}{V_{hb}} C_{2,i} \quad [1]$$

where, V_{hb} is the volume of the headbox (L) and F_j (j = 1, 2, 5 and 7) is the flow rate of each stream (L/min), i.e., F_1 is the thick stock flow rate, F_2 is the flow rate of the stock entering the wire section from the headbox, F_5 is the flow rate of recirculating white water and F_7 is the flow rate of filler slurry.

The flow rate at the headbox F_2 is controlled by the valve located just before the headbox. Hence, the flow rate of the recirculating white water is determined from the headbox flow rate and the flow rate of other input stream such as the thick stock flow and the filler flow:

$$F_5 = F_2 - (F_1 + F_7 + F_{pol} + F_{mp}) \quad [2]$$

where F_{pol} is the flow rate of polymer solution and F_{mp} is the flow rate of microparticle suspension.

From the mass balance on the wire, the first-pass retention of solid materials R_i (i = fines, filler and fiber) is defined as the ratio of the mass of the solids in the wet web leaving the wire section to that in the stock
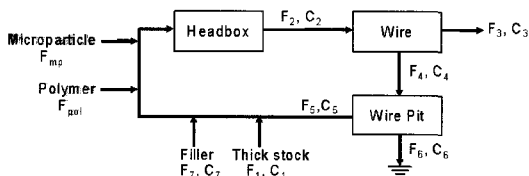

Fig. 2. Block diagram for the wet end of a paper machine.

entering the wire section (i.e., in the headbox):

$$R_i = \frac{F_3 C_{3,i}}{F_2 C_{2,i}} \quad [3]$$

where F_3 represents the flow rate of the wet web leaving the wire section and C is the consistency of each flow (g/L). Since $F_2 = F_4 + F_3$ and $F_4 \gg F_3$, we could assume that $F4 = F2$. Then, the consistencies of white water $C_{4,i}$ (i = fines, filler and fiber) from the white water tray under the wire to the wire pit can be calculated with:

$$C_{4,i} = (1 - R_i)C_{2,i} \frac{F_2}{F_4} = (1 - R_i)C_{2,i} \quad [4]$$

The white water total consistency ($C_{4,total}$) and the headbox total consistency ($C_{2,total}$) are then given by:

$$C_{j,total} = C_{j,fiber} + C_{j,filler} + C_{j,fines} \ (j = 2 \text{ and } 4) \ [5]$$

The dynamics of the recirculating white water consistency $C_{5,i}$ are obtained from the mass balances around the wire pit:

$$\frac{dC_{5,i}}{dt} = \frac{F_4 C_{4,i}}{V_{wp}} - \frac{F_4}{V_{wp}} C_{5,i} \quad [6]$$

where V_{wp} is the volume of the wire pit and F_4 is the flow rate of the white water from the white water tray to the wire pit. Assuming ideal mixing, $C_{5,i} = C_{6,i}$.

The mass flow rate of solid materials leaving the wire section can be calculated with:

$$F_3 C_{3,i} = R_i F_2 C_{2,i} \ (i = \text{fiber, fines and filler}) \quad [7]$$

The ash content of the web (*Ash*) leaving the wire section is:

$$Ash(\%) = \frac{F_3 C_{3,filler} \times 100}{F_3 (C_{3,fiber} + C_{3,fines} + C_{3,filler})} \quad [8]$$

Assuming that there is not any loss of solids at the press and the drying sections, this can be used to represent the ash content of paper. The basis weight of paper (*BW*) is:

$$BW(g/m^2) = \frac{F_3(C_{3,fiber} + C_{3,fines} + C_{3,filler})}{ms \cdot W \cdot r_s} \quad [9]$$

where ms stands for the machine speed (m/min), W is the width of dry sheet after calendering (m) and r_s is the shrinkage rate of the wet web, which is defined as:

$$r_s = \frac{\text{width of dry sheet after calendering } [m]}{\text{width of wet web before pressing } [m]} \quad [10]$$

It should be noted that the first-pass retention (R_i) was included in Eqs. [4] and [7]. First-pass retention is directly influenced by wet-end chemistry factors such as the type and the dosage of retention aids, pH, cationic demand, conductivity and the degree of refining. Hence, implementing thefirst-pass retention into the model makes it possible to relate the wet-end chemistry effect to the output variables such as the white water consistency and the paper ash content. The expression for first-pass retention can be developed by two approaches: a first-principles model and an empirical model. At this point no reliable theoretical model exists to predict first-pass retention from operating conditions. Thus, a simple, yet accurate way is still to perform a series of experiments and to obtain an empirical model for the first-pass retention. In this study, filler retention was measured and the empirical model was developed by nonlinear regression, which is expressed as a function of the mass flow of CPAM, bentonite, pulp and filler.

$$R_{filler} = a_1 M_{pulp} + b_1 C_{filler} + c_1 M_{pol}^2 + c_2 M_{pol} +$$
$$d_1 M_{mp}^2 + d_2 M_{mp} + g_1 M_{pulp} M_{pol} + g_2 M_{pulp} M_{mp} \quad [11]$$
$$+ g_3 C_{filler} M_{pol} + g_4 M_{pol} M_{mp} + e$$

where M_{pulp} is the mass flow rate of pulp in the thick stock (g/min), C_{filler} the filler addition (g of filler/g of pulp), M_{pol} the mass flow of polymer (g/min), M_{mp} the mass flow of microparticle (g/min), and a_1, b_1, c_i, d_i, g_i and e are constants. Since industrial paper machines are operated in narrow operating constraints, this simple approach can be a feasible solution to include the wet end chemistry effects.

Formation of paper is mainly affected by the crowding number (N_{crowd}), the bridging strength (S_b) and the filler concentration in the wet end (11), assuming that the type of furnish and retention aids are chosen before papermaking, that the basis weight and the ash content of paper are decided for a given grade and that the shear in the headbox and on the wire section are optimized for a given grade and for a given paper machine. The filler in the headbox also affects fiber flocculation. Thus, formation can be modeled as a function of those parameters. An empirical model was developed to predict formation index (ROD) and to simulate the dynamics of formation.

$$FI(ROD) = a_1 S_b^2 + a_2 S_b + b_1 e^{b_2 N_{crowd}} +$$
$$cC_{filler} + dS_b N_{crowd} + e \quad [12]$$

where a_i, b_i, c, d, and e ($i = 1$ and 2) are constants. The detailed models and discussions on calculating the crowding number and the bridging strength can be found elsewhere (11, 12).

3. Experimental

The furnish onsisted of softwood bleached Kraft pulp. It was refined to a freeness of 360 mL CSF. The pH of the furnish was adjusted at 7.5 by adding sodium hydroxide to the stock chests. Precipitated calcium carbonate (PCC, 30% slurry, Albacar HO) was mixed with pulp at the blend chest (17% filler content in thick stock) for uniform mixing. A cationic poly (acrylamide) (CPAM, Allied colloids, Percol 292) of medium molecular weight (- 5×10^6) and with a degree of substitution of 25% was used as received. CPAM was diluted to a concentration of 1.5 g/L. A commercial bentonite (Hydrocol O, Allied Colloids) was also used as received. The bentonite was dispersed at a concentration of 3 g/L. The CPAM solution was injected at the inlet of the pressure screen and the bentonite solution was added at the screen outlet.

To investigate the effect of the process variables on

the dynamics of the wet end, step changes were applied to the CPAM dosage, the bentonite dosage, the fiber concentration, the initial filler concentration and the headbox flow rate. Only one variable was changed at a time. The dynamics of basis weight, ash content and formation were measured by on-line sensors (ABB) after calendering. The dynamics of headbox total and filler consistencies and white water total and filler consistencies were measured by Kajaani Rmi sensors. Typically, basis weight is automatically controlled by regulating the thick stock valve located after the machine chest, and moisture content by steam pressure of driers. The control system of the pilot paper machine is ACCURAY1190-ABB. However, in our experiments, the basis weight control loop was turned off.

4. Results and Discussion

The dynamics of the wet end and the dry end were simulated by solving the nonlinear models presented using the MATLAB/SIMULINK software. For the simulation, the first-pass retention of fiber was assumed to be unchanged by the perturbations: the value of 0.97 was used. Also, it was assumed that the first-pass retention values of fines and filler are identical ($R_{fines} = R_{filler}$).

Fig. 3 shows the effects of retention aids on the dynamics of the headbox and the white water total consistency and the basis weight, the ash content and the formation of paper. The changes in the white water consistency and the paper ash content were caused by the changes in the filler retention. When the first-pass retention of filler decreased, the white water consistency was increased and the paper ash content and the basis weight decreased, and *vice versa*. The magnitude of variations of the recirculated white water consistency is relatively smaller than the magnitude of noises of headbox consistency. Hence, small variations in the headbox total consistency were observed. The
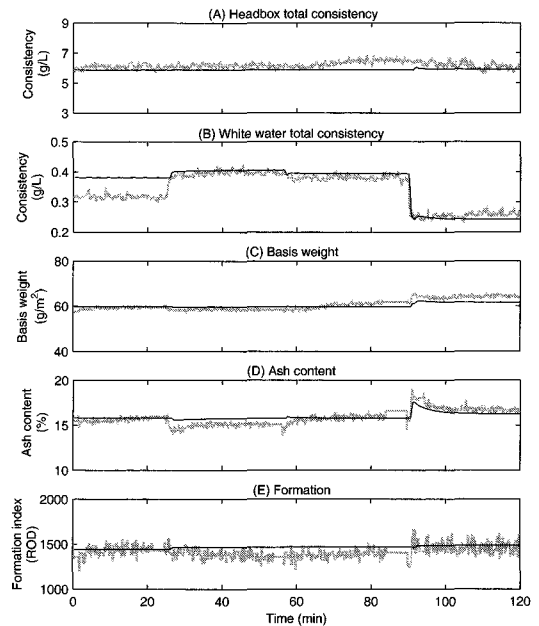

Fig. 3. Effects of dosages of retention aids on the dynamics of a paper machine At 0 min, CPAM = 0.2 mg/g and bentonite = 1 mg/g; at 25 min, CPAM = 0.2 mg/g and bentonite = 0 mg/g; at 56 min, CPAM = 0.35 mg/g and bentonite = 0 mg/g; at 89 min, CPAM = 0.35 mg/g and bentonite = 2 mg/g. The black line represents the simulated data and the gray line, the experimental data.

changes in formation were caused by the changes in the bridging strength (11).

Fig. 4 shows the effects of thick stock flow rate. When the thick stock flow rate was decreased, the headbox consistency decreased and hence the white water consistency and the basis weight of paper were decreased, and *vice versa*. Filler was mixed with pulp at the blend chest: i.e., the mass ratio of filler to pulp kept constant. Also, the variations in filler retention due to the changes in the mass flow rate of pulp were very small (13). Hence, the ash content of paper was observed to be almost constant. The changes in formation are due to the changes in the crowding number (11).
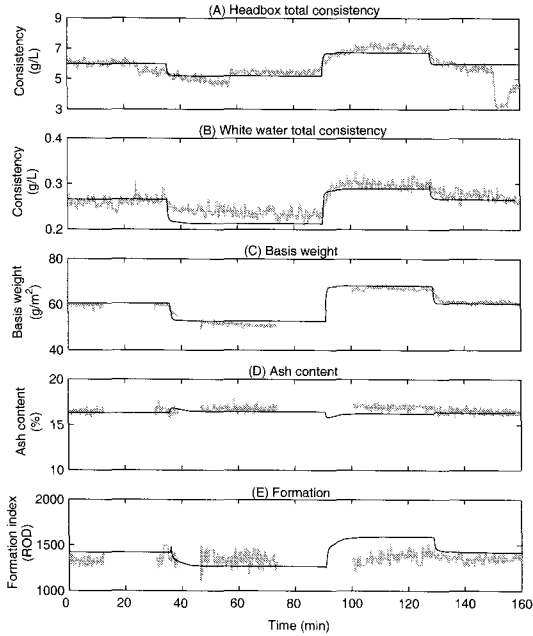
Fig. 4. Effects of the thick stock mass flow rate on the dynamics of a paper machine At 0 min, Thick stock mass flow rate (M_1) = 1840 g/min; at 35 min, M_1= 1580 g/min; at 90 min, M_1 = 2100 g/min; and at 128 min, M_1 = 1840 g/min. The black line represents the simulated data and the gray line, the experimental data.
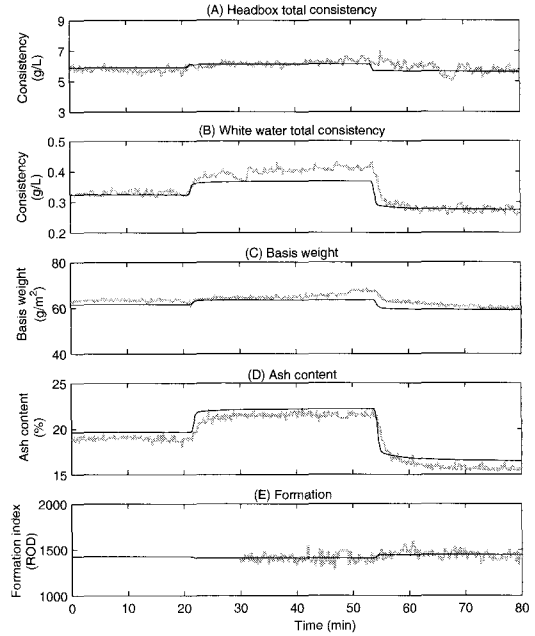
Fig. 5. Effects of the filler addition on the dynamics of a paper machine At 0 min, filler addition (C_{filler}) = 0.25 g/g; at 19 min, C_{filler} = 0.30 g/g; and at 54 min, C_{filler} = 0.20 g/g. The black line represents the simulated data and the gray line, the experimental data.

The effects of filler addition (g/g of pulp) on the dynamics of a paper machine are shown in Fig. 5 When the filler addition increased, the headbox total consistency, the white water total consistency, the basis weight and the ash content were increased and *vice versa*. When filler addition decreased at 54 min, formation index slightly increased.

Fig. 6 shows the effects of the white water flow rate F_5 on the dynamics of a paper machine.The recirculated white water flow rate was manipulated by changing the headbox flow valve (F_2). When the headbox flow rate was decreased at 25 min, keeping the thick stock flow F_1 constant, the recirculated white water flow F_5 decreased. This resulted in the increase of the headbox total consistency and the white water

total consistency. Because of the sudden decrease of the headbox valve opening, the basis weight dropped sharply and recovered to its original value. Discrepancy is found between the experimental results of the basis weight and the simulated one (Fig. 6-(C)): the experimental results showed a high peak. This could be explained by a nonuniform mixing at the pipeline between the headbox and the headbox valve and at the headbox, while an ideal mixing was assumed in simulation. The filler addition was kept constant for this set of experiments, which resulted in constant ash content. The changes in formation of paper are due to the changes in headbox fiber consistency, which affect the crowding number. Some discrepancies are found in Fig. 3, 4, 5 and 6, but the experimental data and model predictions show relatively good agreement.
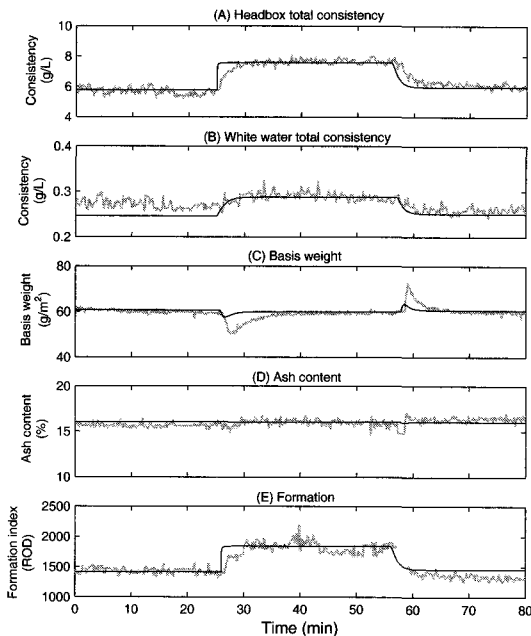
Fig. 6. Effects of the white water flow rate on the dynamics of a paper machine At 0 min, headbox flow rate (F_2) = 340 L/min; at 25 min, F_2 = 245 L/min; and at 57 min, F_2 = 320 L/min. The black line represents the simulated data and the gray line, the experimental data.

5. Conclusions

Dynamic models of a pilot paper machine for the retention process including headbox total and filler consistencies, white water total and filler consistencies, the basis weight and the ash content of paper were developed from first-principles (mass balances). To describe the wet end chemistry effect, first-pass retention was included in the model as a parameter dependent on operating conditions. In addition, an empirical model for formation was developed as a function of the crowding number, the bridging strength and the filler fraction in headbox stock and implemented into the dynamic simulation models. It was shown that the dynamics of retention and formation processes of a paper machine can be

simulated using the mathematical models describing the mass balances of solids in the paper machine coupled with empirical models of the first-pass retention and the paper formation.

Acknowledgement

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