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

Yeong-Koo Yeo†, Sung Chul Yi, Jae Yong Ryu and Hong Kang*

Dept. of Chemical Engineering, Hanyang University, Seoul 133-791, Korea
*J. J. Engineering, Kwangjin-Ku, Seoul 143-200, Korea
(Received 23 July 2003 • accepted 14 October 2003)

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 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].

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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 \( Q_a \), the ash fraction of the thick stock \( X_{a0} \) and the flow rate of the retention aid \( Q_p \) are as-
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 $p_1$ as

$$p_1 = k \cdot P_s \cdot S_s \cdot J \cdot C_r \cdot 1000$$  \hspace{1cm} (1)

where $S_s$ and $P_s$ are the width of the slice and the pond, respectively, and $C_r$ is the headbox slice factor which is dependent upon the configuration of the outlet device of the headbox. The product $P_s \cdot S_s \cdot C_r$ gives the area of the headbox outlet section. $J$ 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, $J_s$ 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

$$Q_s = p_1 \cdot V_s$$  \hspace{1cm} (2)

where $V_s$ 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

$$Q_p = \frac{p_1 \cdot V_s \cdot C_r \cdot R}{C_w}$$  \hspace{1cm} (3)

where $R$ is the retention ratio, $C_w$ is the consistency in the headbox and $C_r$ is the consistency of the stream to the press. $C_r$ lies in the range of 18-22% and is set to 20% in the simulations. The product $p_1 \cdot V_s \cdot C_r$ 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

$$Q_t = Q_s - Q_p = p_1 \cdot V_s \cdot \frac{p_1 \cdot V_s \cdot C_r \cdot R}{C_w}$$  \hspace{1cm} (4)

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

$$Q_{sa} = Q_s - Q_p$$  \hspace{1cm} (5)

$Q_t$ is the flow rate of the internal circulation stream and is given by

$$Q_t = Q_s - Q_p - Q_r - V_s$$  \hspace{1cm} (6)

where $V_s$ 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

$$\frac{dC_s}{dt} = (1 - R_s) \cdot Q_s \cdot C_s - Q_p \cdot C_s + Q_{sa} \cdot C_s$$  \hspace{1cm} (7)

$$\frac{dX_{sa}}{dt} = (1 - R_s) \cdot Q_s \cdot X_{sa} - Q_p \cdot C_s \cdot X_{sa} + Q_{sa} \cdot C_s \cdot X_{sa}$$  \hspace{1cm} (8)

where $C_s$ is the silo consistency, $X_{sa}$ is the ash fraction in the silo and $R_s$ is the ash retention. $V$ denotes the total volume of the silo and the seal pit. Similarly, the dynamics in the stock approach section are given by

$$\frac{dC_f}{dt} = Q_f \cdot C_f + Q_s \cdot C_f - Q_p \cdot C_f$$  \hspace{1cm} (9)

$$\frac{dX_{sa}}{dt} = Q_f \cdot X_{sa} + Q_s \cdot C_f \cdot X_{sa} + Q_p \cdot C_f \cdot X_{sa}$$  \hspace{1cm} (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 $V_t$ to represent the stock approach section. We assumed that the flow from the tank becomes the outlet flow from the headbox. $V_t$ 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 $R_a$ as

$$\frac{dR}{dt} = \frac{k_1}{\tau} \cdot Q_s - \frac{R}{\tau}$$  \hspace{1cm} (11)

$$\frac{dR_a}{dt} = \frac{k_2}{\tau} \cdot Q_s - \frac{R_a}{\tau}$$  \hspace{1cm} (12)

where $\tau$ is the retention time constant, $k_1$ is the retention constant and $k_2$ is the ash retention constant. $k_2$ was assumed to be 1/3 of $k_1$. $k_1$ can be obtained from the steady-state retention and the amount of the retention aid. $\tau$ depends on the specific paper machine being used.

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

$$BD = Q_s \cdot C_s \cdot R \cdot (C_f / p_f) \cdot w_s \cdot 1000 / (V_s \cdot \tau_s)$$  \hspace{1cm} (13)

$$ashBD = Q_s \cdot C_s \cdot X_{sa} \cdot R_s (C_f / p_f) \cdot w_s \cdot 1000 / (V_s \cdot \tau_s)$$  \hspace{1cm} (14)

where $C_s$, and $p_f$ are widths of the couch and the pond, respectively, and $r_s$ is the reel width. $w_s$ 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) $k_1$ is defined as $k_1 = R_s / Q_p$, i.e., $k_1$ is defined as the initial retention divided by the reteino aid rate.

ii) The retention shows 1st-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 1st cleaner accept, deculator outlet, 1st screen accept, and headbox outlet do not show large discrepancy.

iv) Thick stock ash fraction is constant.