Potential Application of Predictive Tensile Strength Models in Paper Manufacture: Part II – Integration of a Tensile Strength Model with a Dynamic Paper Machine Material Balance Simulation

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ABSTRACT

A new semi-empirical version of the Page Equation has been developed. The model was found to provide good predictions of the machine direction and cross direction tensile strength of paper produced on the Miami University pilot paper machine. The effects of refining, filler level, cationic starch level, and fiber properties are included in the model. A way to integrate the model with a dynamic material and energy balance simulation of a paper machine is described and potential papermaking applications suggested.

INTRODUCTION

The Generic Problem of Dead Times in Papermaking

The significant dead times that exist in a papermaking system present process control challenges. Fig. 1 illustrates a typical situation. The times given at the bottom of the figure refer to mean tank (chest) residence times. The time associated with the reel is one-half the time required to build a typical reel of paper (40 minutes).

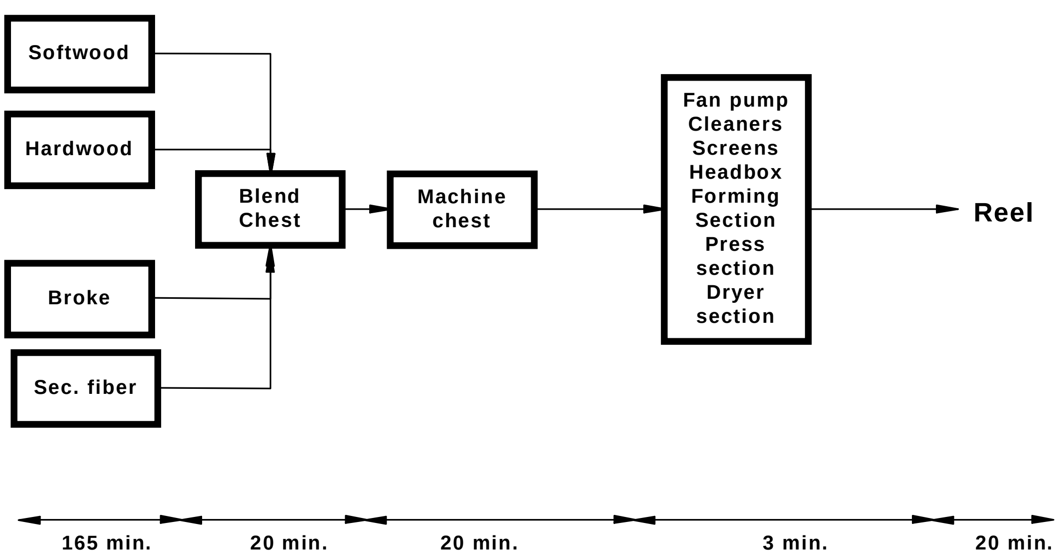

Figure 1. Typical mean chest residence times throughout a papermaking system

It can be inferred from the figure that a disturbance in any of fiber supply chests might not appear in the produced paper for over three hours. During that time the operator will be unaware that anything has occurred and the system will fill with problem stock. If the paper quality of interest is not monitored on-line, the reel build time must also be added, along with the off machine sampling and testing times, thereby the total to nearly four hours.

The above discussion represents a worst-case scenario. Disturbances occurring from the blend chest forward will involve shorter dead times and the production of smaller amounts of off-quality paper. On the other end of the scale, the twenty-three minutes associated with the thin stock system and reel building represents a minimum dead time in cases where no on-line sensor is available and off-line testing is done. A considerable amount of off-quality paper can be produced in that length of time by a high-speed machine.

The specific case of tensile strength

Tensile strength is a good example of a case where no on-line sensor is commonly employed and where the operator relies upon feedback from off-line tests run once per reel. Consequently, the possibility exists of producing large amounts of off-quality paper as described above.

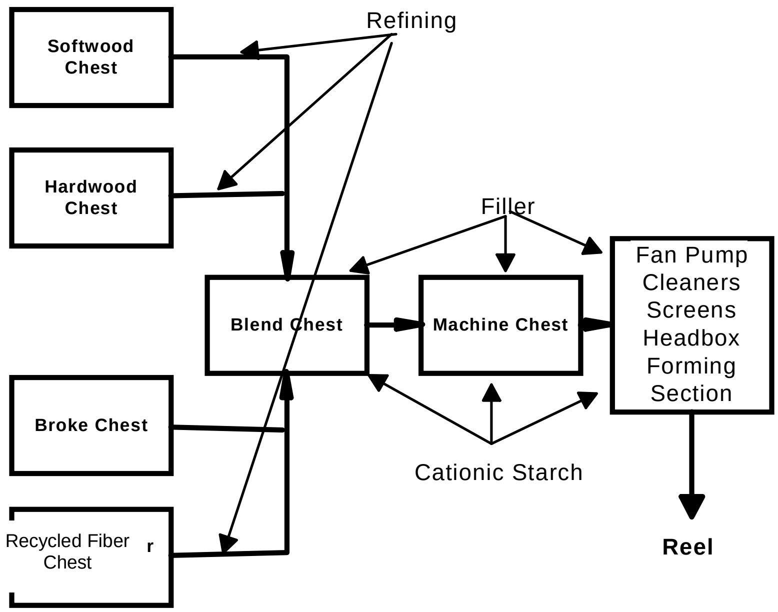

Figure 2. Paper machine schematic diagram illustrating chemical additive addition points.

In addition to the dead times associated with stock inputs and flows, the effects of other variables must also be taken into account. Refining, filler levels, and dry strength agents are the most common variables of interest and their dead times will depend on their addition points (Fig. 2). Thick stock addition points will have dead times of 40-60 minutes. Thin stock addition points dead times are very small (<3 minutes) and off-quality paper problems will be mainly associated with paper collected on the reel.

On-line sensors for the measurement of strength properties exist, but they have not been widely adopted by papermakers. It is more usual to test manually a strip of paper from a completed reel. The results are then entered into a logbook or a computer process information database system. In this instance, it would be realistic to add the testing time to the process dead times and reel building time to have a complete picture of how long it might take to discover that off-quality paper is being produced.

Alleviating the Problem Through the Use of a Semi-Empirical Tensile Strength Model

Systems having long dead times can benefit greatly from the application of predictive models that provide real-time, or faster than real-time, performance predictions that an operator can use to inform his/her control actions or can be used as part of an advanced process control scheme. These models are often called “soft sensors” or “virtual sensors” because they provide values (or “signals”) that can be used in the same way as signals from an on-line sensor. For example, one could arrange to have a model compute and display paper tensile strength at the very instant it is being added to the reel, just like a dry-end sensor would do. Or, one could speed up the calculation and have the prediction appear ahead of reel-up time. In the former instance, one would "save" the time associated with reel building. In the latter case, one would also reduce the effect of thick stock dead times if the calculations were timed accordingly.

To illustrate an example of the latter case, let us take an instance where a change in softwood refining occurs (Fig. 3). If the thick stock dead times are the same as in Fig. 1, then it will be about forty-three minutes until the refining change shows up at the dry end in the form of altered tensile strength. It might also take an additional thirty minutes, on average, until the paper is tested and the tensile change discovered. Thus, at least seventy-three minutes of off-tensile paper will be produced.

Much of the off-quality production could be avoided if a predictive calculation were done very soon after the refining change occurred. This calculation would predict the tensile strength change and alert the operator that something is wrong. The total off-quality paper produced would depend upon how fast the operator solves the problem and how long it takes the system to return to normal operation. Fig. 4 presents an example of this situation. (Note that the same system of programs that predicts tensile strength could also be structured to aid an operator in trouble-shooting and solving the problem.)

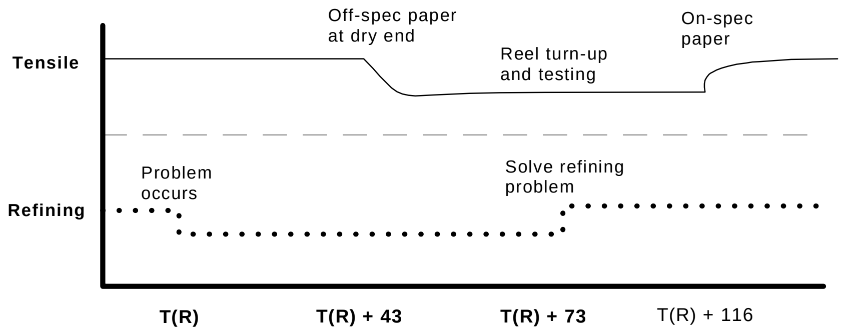

Figure 3. Schematic illustration of off-quality paper production in the absence of a predictive model or on-line sensor. A total of 73 minutes of off-quality paper would be produced. It is assumed that the refining problem gets solved as soon as it is discovered.

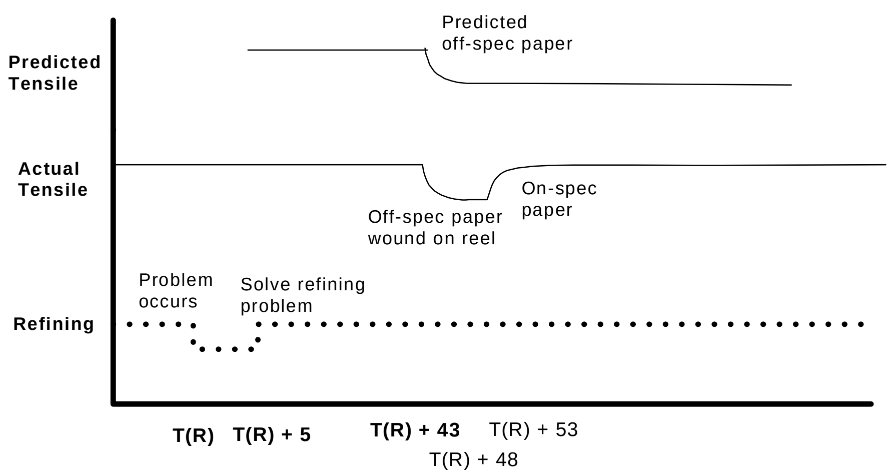

Figure 4. Schematic illustration of off-quality paper production in the presence of a predictive model. A total of 5 minutes of off-quality paper would be produced. It is assumed that the predictive calculation occurs much faster than real-time. It is further assumed that the refining problem gets solved as soon as it is discovered.

METHODS

The need to have a dynamic paper machine simulation combined with the tensile strength model

It would be insufficient to utilize only a steady state tensile model because the inputs and outputs around a paper machine system vary from minute to minute. Tank capacitances, stream mixing and recycle loops must be accounted for. Wet end chemistry interactions such as fines retention and cationic starch adsorption by fines and filler need to be taken into account. It becomes clear that a complete modeling system must contain a dynamic simulation of paper machine material flows, as well as a specific model that relates process and raw material inputs to tensile strength. This is the approach to be followed here.

Empirical Models

The empirical models for tensile strength found in the literature are either regression models or neural network models that relate sets of fiber properties or process variables to strength. Empirical models have several disadvantages in cases where multiple variables are involved. First, even the simplest linear regression model requires at least one constant coefficient for every variable in the model and the values for these constants must be determined from experimental data. In general, you need as many independent data sets as there are constants in order to solve for their values. You also need to do additional data sets to learn the effect of random experimental error.

This is not a straightforward matter when a system as complex as a paper machine is involved. Papermakers are highly reluctant to run the types of experiments needed to determine regression model coefficients on their machines.

A second disadvantage is that empirical models are not very robust with respect to changes in process configuration or raw material inputs. Consequently, a new set of model coefficients must be experimentally determined every time a significant modification is made to the process or raw materials.

First Principles Models

First-principles models represent the other end of the spectrum. These models would appear to be more desirable because they ought to be more robust and not require the determination of empirical constants. For this to be true, however, the model must take every aspect of process into account. This is practically impossible for systems as complicated as a paper machine. A second drawback is that there are very few generally accepted first-principles models of papermaking phenomena available to the papermaker.

Semi-empirical Models

A semi-empirical approach is the most attractive alternative in cases where a model must account for the effects of multiple independent variables because semi-empirical models typically contain only has a few constants to be determined. These constants can serve as a way to “calibrate” the model to fit different systems. Also, it is usually easier to understand and “trust” semi-empirical models because they retain a first-principles form.

Development of A Semi-Empirical Version of the Page Equation

The goal of this research project was to predict the tensile strength of paper from certain raw material and process knowledge by using a new form of the Page Equation. The Page Equation for the tensile strength of paper [1]has the following form.

(i) $1/T= (9/8Z) + (3w_f/RBA.\tau_b l_f)$

where

Z = zero span tensile strength, reflecting fiber strength.
τ_b = breaking stress of bonds (breaking force over bond area)
w_f = fiber width
l_f = fiber length
RBA = Relative bonded area

The following assumptions and procedures employed to convert Eq. (i) into a useful form for process control in the paper mill are described in Part I of this series [2].

- Fiber width, w_f, was assumed to be constant for the various types of fibers present.
- Zero span tensile strength, Z, was converted to a function, Z(CSF), determined from data collected by measuring the zero span tensile strength for different pulps at a series of freeness values.
- Fiber length, l_f, was also converted to a function, l_f(CSF), determined from data collected by measuring the average fiber length for different pulps at a series of freeness values.
- The term, (RBA.τ_b), was replaced by Cowan's B factor [3] as determined for different pulps at a series of freeness values. This produced a new function designated B(CSF).
- Correction terms for filler and cationic starch were also developed.
- The two major parts of Eq. (i) were assigned a calibration constant to be determined from paper machine system data.

It should also be noted that our treatment ignored the effects of fiber length distribution, fiber orientation, machine draws, and dryer performance – all of which can influence tensile strength. Future work will address these issues.

The final modified Page Equation is presented in Eq. (ii).

(ii) $1/T = K1/ Z(CSF) + K2\ w_f /[[(1-s_f)\ (1+7.44X_{cs})]\ B(CSF)\ l_f(CSF)]$

X_{cs} the mass of cationic starch added per unit mass of fibers.
s_f the fraction of the relative bonding area reduced by the addition of filler. To determine this, the respective surface areas of fiber and filler in the produced paper were calculated. The specific average surface area used for fibers was 2 m^2/g and for filler (calcined clay) 4.3 m^2/g.
B(CSF) Cowan's B factor, which is a measure of the total bond strength, as a function of CSF
Z(CSF) Zero span tensile strength as a function of CSF
lf(CSF) Average fiber length as a function of CSF

The calibration constants, K1 and K2 in Eq. (ii) were determined from tensile strength data collected on the Miami University pilot paper machine [4]. The following results were obtained.

MD tensile
(iii) $1/T = 0.0203/\langle Z\rangle + 4.374w_f /[[(1-s_f)(1+7.44X_{cs})]\langle B\rangle \langle L\rangle$

CD tensile
(iv) $1/T = 0.045/\langle Z\rangle + 10.29w_f /[[(1-s_f)(1+7.44X_{cs})]\langle B\rangle \langle L\rangle]$ ….

where,

w_f = fiber width in µm
<L> = mass-weighted average fiber length of hardwood and softwood l_f(CSF) in the furnish, mm
(v) sf = relative surface area reduced by the addition of filler

$$s_f = \frac{[\text{Filler flow rate in formed sheet (mass/time)}]\ [\text{SSA Filler}]}{[\text{Fiber flow rate in formed sheet (mass/time)}]\ [\text{SSA Fiber}]}$$

(vi) X_{cs} = the mass of cationic starch per unit mass of fiber = cationic starch add. rate (lb/ton) ÷ 2000
<Z>, <B> = mass-weighted averages of hardwood and softwood Z(CSF) and B(CSF) in furnish.

Hardwood Z and B:

(vii) $Z(CSF) = -6E\text{-}05(CSF)^2 + .0494(CSF) + 42.072$

(viii) $B(CSF) = -1E\text{-}05(CSF)^2 + .0027(CSF) + 6.9038$

Softwood Z and B:

(ix) $Z(CSF) = -3E\text{-}05(CSF)^2 + .0147(CSF) + 68.316$

(x) $B(CSF) = 2E\text{-}06(CSF)^2 + .003(CSF) + 2.8621$

Fiber lengths

(xi) Hardwood l_f: $l_f(CSF) = 0.7$

(xii) Softwood l_f: $l_f(CSF) = 3.0E\text{-}06\ (CSF)^2 – 0.0015\ (CSF) + 1.629$

Predicted tensile values calculated with Equations (iii) and (iv) were compared to data collected from a second pilot machine run. The two data sets agreed closely. This is discussed in Part I. of this series [2].

DISCUSSION OF A PAPER MACHINE SIMULATION UTILIZING THE SEMI-EMPIRICAL PAGE EQUATION

Introduction

As described above, the approach taken in this project was to combine a dynamic simulation of the material balances around a paper machine with computation of the tensile strength of the produced paper. Consideration of Eqs. (ii) and (iii) reveals that in order to model tensile strength, attributes such as such as fiber lengths, zero span tensile strength and bond strength, will need to be followed in addition to the material flows in system. The tracking of such factors becomes particularly important and difficult when the calculation of a particular phenomenon is a time dependent function of a prior event. For example, changes in refining affect fiber length, zero span tensile, and bond strength, which in turn affect the tensile strength of paper produced at a later time. Therefore, information about changes in fiber length, zero span tensile and bond strength must be passed downstream to the unit operation where paper tensile strength calculations are performed.

Shirt and Manness [5]described an approach to achieve the tracking of attributes. Their methods were adopted in this project. The specific simulation program utilized was the Kodiak® program by Simons Technologies, Inc.

Material Attribute Tracking

In order to describe the state of the material components in a system, the Kodiak® Simulator maintains state variables that quantitatively describe the physical and thermodynamic characteristics of each material. In addition to these basic state variables, the simulator can be configured to track additional attributes that further define the state of the material on a component-by-component basis. These additional attributes are referred to as material attributes. Examples of material attributes include apparent density, fiber coarseness, freeness, fiber length and specific surface area. It is important to note that material attributes differ from mass and energy in the simulator in that they do not always follow the normal conservation laws built into a material balance simulator. Instead, the user must define how material attributes both mix and are transformed in the system.

Processing and Mixing Rules

It is usual that raw materials pass through a series of processing stages that change their nature or state while being converted to a final product. In the simulator, the part of the unit operation affecting the material attributes in each processing stage is represented by an equation called a processing rule. For example, there may be a processing rule that changes the freeness of the fibers that flow through a refiner block. By changing the operating conditions of the refiner in the simulation model, the material attributes (e.g. freeness) of the fibers leaving the refiner will also be changed.

Each material attribute has associated with it a mixing rule that is used in combining two separate streams into a single one with homogeneous material attribute values. Mixing rules govern the conservation of attribute values within the sytem. The following mixing rule was used in the tensile strength simulation calculations:

(xiii) Mass weighted average $\langle x\rangle = \Sigma W_i x_i / \Sigma W_i$

The parameter x_i represents the attribute value for individual material components. The $\langle x\rangle$ parameter represents the mass-weighted average value for the mixture. The W_i are the masses of each individual material component. While processing rules are specific to each unit operation, mixing rules are generic to the entire simulation model.

Combining the Kodiak Paper Machine Simulation and the Tensile Model

Fig. 5 illustrates schematically how processing and mixing rules could be applied in a tensile strength simulation.

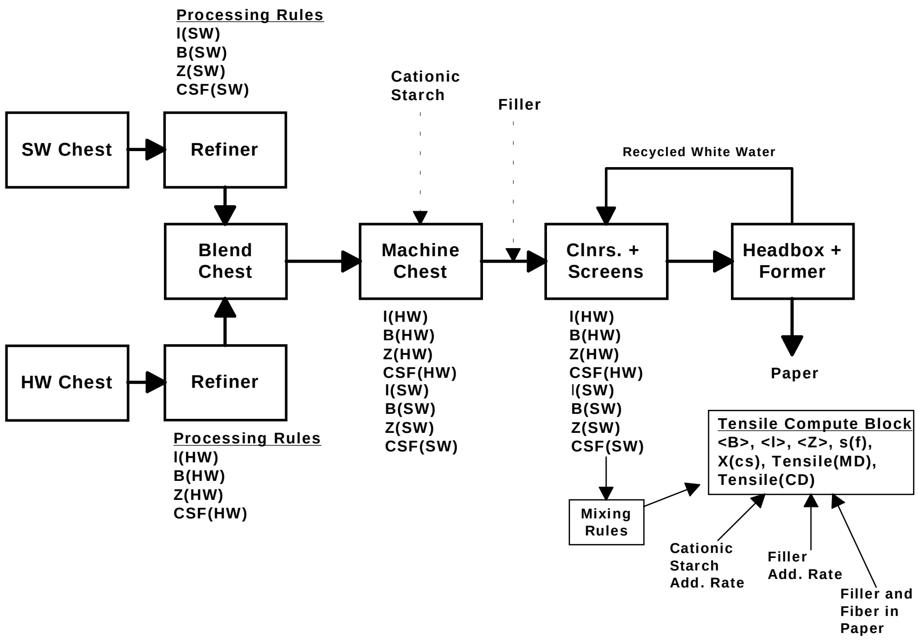

Figure 5. Processing and mixing rules and other non-mass balance calculations required in the tensile simulation.

The tensile computations begin with computation of CSF values for the refined hardwood and softwood pulps from refiner operating parameters. These values are passed to computational blocks where l_f(CSF), Z(CSF), and B(CSF) are computed for hardwood and softwood from Eqs. (vii) – (xii).. These attributes travel with the hardwood and softwood to the blend chest and then through to the machine chest.

In the machine chest, cationic starch is added and X_{cs} is computed from the cationic starch addition rate using Eq. (vi). l_f(CSF), Z(CSF), and B(CSF) are carried through to the thin stock system along with X_{cs}.

Filler is added just after the fan pump. The stock travels through the approach flow system and onto the forming section where the sheet is formed. The filler and fiber flow rates in the formed sheet, along with specific surface area values are used to compute s_f. Finally, mixing rules are applied to compute $\langle Z\rangle$, $\langle B\rangle$, and $\langle L\rangle$. Tensile strength is then computed for the formed paper from these values, X_{cs} and s_f.

Applications of the Combined System

Table I lists some potential applications for the tensile simulation system and other, similar simulation systems.

Table I
Potential applications for the tensile simulation system

Monitoring paper quality (soft sensors)

- open-loop feedback
- data logging for future off-line analysis

Predictive Quality Control

- anticipating quality problems

What If/Advisory Mode

- Trigger at any process operator change or input change
- Advisory system:
    - e.g. drainage problems -> possible change in refining ->effect on tensile?

Closed-loop Control (future)

- feedback / feedforward
    - adjust cationic starch addition to insure uniform and optimized tensile
    - reduce cationic starch usage rates
    - need to develop confidence in model to implement closed-loop control

The first three types of applications listed above could be implemented directly once a reliable tensile simulation system is developed. The implementation of closed-loop control applications would be feasible after sufficient experiment is gained with the model.

Setting up the Tensile Simulation System in the Mill

The six-step process presented in Table II would be required in order to implement this tensile simulation in the mill.

Table II
Six-step process required to implement the tensile simulation system

1. Collect B, Z and fiber length data for pulps at a series of CSF values
2. Develop a mass balance simulation of the paper machine system from P & ID diagrams and process data
3. Add the tensile model to the paper machine simulation to create the tensile simulation system
4. Determine values for the two tensile model calibration constants from historical mill data or trial data.
5. Interface the tensile simulation system with the machine’s data archiving system
6. Test the system.

Concluding Remarks and Future Directions

It is recognized that the tensile simulation system discussed in this paper contains several simplifications and assumptions. Future factors to be addressed in the model include dryer and draw variables and fiber length distribution. Interactions with fines retention and cationic starch adsorption should also be added to the system.

Future paper quality models to be developed and incorporated in the simulation include appearance properties, wet strength, wet web strength, and sizing. Drainage is an important machine parameter that should be added as well.

REFERENCES

[1] Page, D. H. *A theory for the tensile strength of paper*. Tappi J., 52: 4, 674 (1969).

[2] Garg, P. and Scott, W. E. *Potential Application of Predictive Tensile Strength Models in Paper Manufacture: Part I – Development of a Predictive Tensile Strength Model from the Page Equation*. Accepted for presentation at the 2001 TAPPI Papermaker's Conference.

[3] Wavell F. Cowan. *Explaining handsheet tensile and tear in terms of fiber-quality numbers*, Tappi J., 78: 1, 101-106 (January 1995).

[4] Garg, Pankaj. *The development of a modified Page Equation for use in papermaking process control.* M. Sc. Thesis. Paper Science and Engineering, Miami University, 1999.

[5] Shirt, R. and Manness, M. *Dynamic simulation of retention chemistry effects using a material attribute array structure.* TAPPI Engineering Conference Proceedings, Atlanta, GA, February 1999.