A mechanistic model for predicting pulp properties from refiner operating conditions

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ABSTRACT: A mathematical model for a refining process is presented. The model predicts pulp properties (freeness, long-fiber content, and shive content) and handsheet properties (burst index, tensile index, tear index, and light-scattering coefficient) based on refiner operating conditions and process disturbances. The operating conditions include transfer-screw speed (production rate), refiner closing pressure (specific energy), and dilution flow rate (consistency). The process disturbances include variations in chip bulk density and moisture content. The model also considers the effects of refining intensity and refining power on pulp and handsheet properties.

KEYWORDS: Chips, hand sheets, mathematical models, refiner mechanical pulping, pulp properties, quality, refiner mechanical pulping, refining, simulation, paper properties.

The refining process has been the subject of many theoretical and experimental studies, but mathematical models of the refining process remain in short supply. This work presents a mathematical model of the refining process for CTMP (chemithermomechanical pulp). The model predicts pulp and paper properties based on refiner operating variables and process disturbances.

A CTMP process generally comprises three operations: wood-chip pretreatment, chip refining, and pulp processing.

The pretreatment process involves screening to remove oversize and undersize chips; washing to remove contaminants; presteaming to drive off air entrapped in the chips; impregnation with sodium sulfite; and heating in the steaming vessel before feeding the chips into the refiners.

The refining process is usually carried out in two stages, as seen in **Fig. 1**. Chips are introduced into the eye of the primary refiner, and the material is progressively broken down into fibers and fiber fragments as it moves through the refining zone between the revolving plates. Refining consistency is adjusted by the water supply to the eye of the refiner. The primary refiner is usually operated under pressure, and the refined material is blown into a cyclone, where fibers and steam are separated. Fibers are refined further in a secondary refiner, which usually operates at a lower pressure than the primary refiner. Another cyclone after the secondary refiner separates fibers and steam. The pulp is then sent to a latency chest, where it is mixed with hot water for latency removal and dilution.

Model development

Refiner model

The first step in developing a mathematical model of a process is to select the relevant variables. **Figure 2** shows the variables that were selected to represent the refiner operating conditions and the pulp properties.

Primary variables. Clearly, many of the refining variables can be ad-

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justed either by the control system or by the refiner operator. For example, the closing pressure can be used to adjust the axial thrust of the plates or the plate gap on some types of refiners. Similarly, the rotational speed of the transfer-screw feeder can be used to alter the wood-chip feed rate, thus controlling the production rate. Finally, the dilution flow rate can be used to control the inlet consistency and thus the refining consistency.

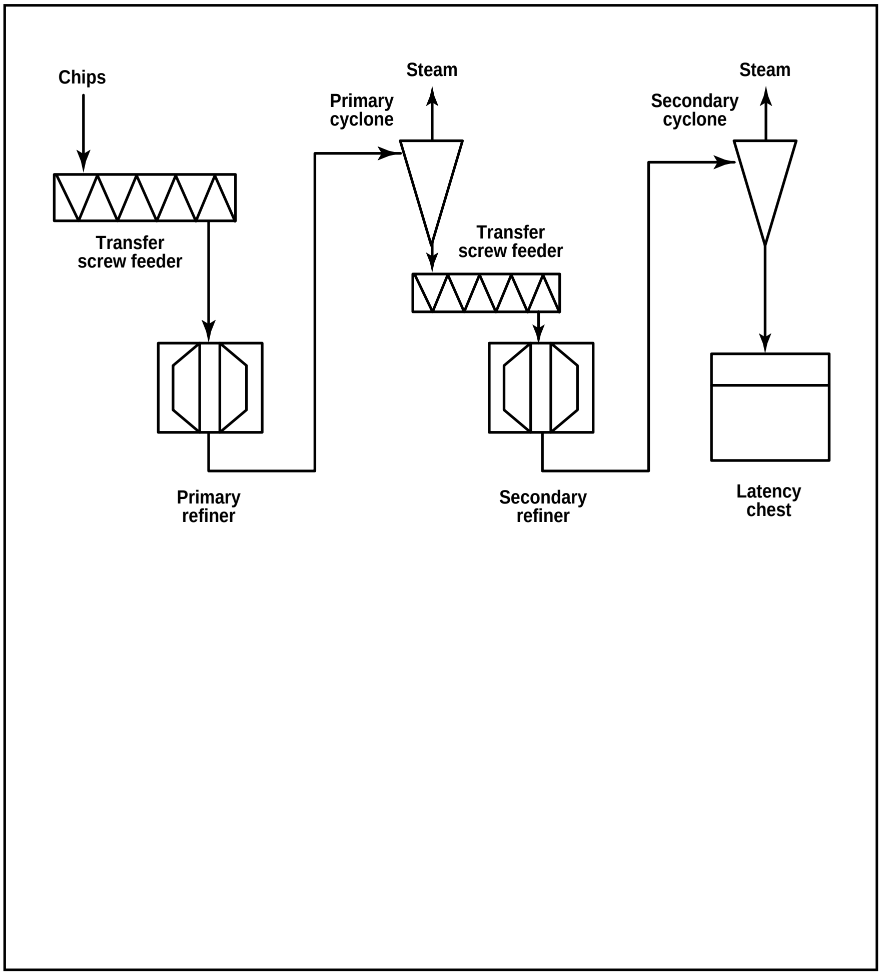
Secondary variables. Additional variables are often used to describe the operating conditions of a refining system. Such variables include refining consistency, specific energy, refining intensity, etc. In this study, these are called secondary variables, since they can be calculated from the primary variables and operating conditions.

Process disturbances. Refining processes are subject to various disturbances. The major disturbance is variation in the wood supply (species, chip size, bulk density, moisture content, etc.). Variations in the chip pretreatment process (steam temperature, residence time, etc.) are also disturbances, but to a lesser extent. The characteristics of the refiner can also change slowly with time, for example as a consequence of plate wear.

Passive variables. Different refiner installations will result in different system characteristics. One well-known variable is the rotational speed of the refining discs, which has a significant effect on product quality and energy consumption. However, most industrial installations have a fixed rotational speed, so this was not taken as a manipulated variable in this study.

Output variables. The aim of refining is to produce pulp with specified properties. In this work, pulp freeness, long-fiber content, and shive content were used to evaluate refiner performance, since these variables can be measured on-line. Fiber specific surface or fiber flexibility could also be used as output variables.

1. Chip-refining process



The model for the refining process consists of three major steps, as seen in Fig. 2. The first step relates the operating variables and disturbances to the secondary variables. The second step relates the secondary variables and the output variables (pulp properties). The third step uses an empirical model to relate the pulp properties to the handsheet properties.

Production rate

Wood chips are fed to the refiner by a transfer-screw feeder. The volumetric flow rate of chips, F_C, is adjusted by changing the speed of the transfer-screw feeder, TS. In practice, a factor of proportionality is used to relate the rotational speed to the production rate. The production rate can then be expressed as the function of both the transfer-screw feeder speed and the chip bulk density, ρ, as follows:

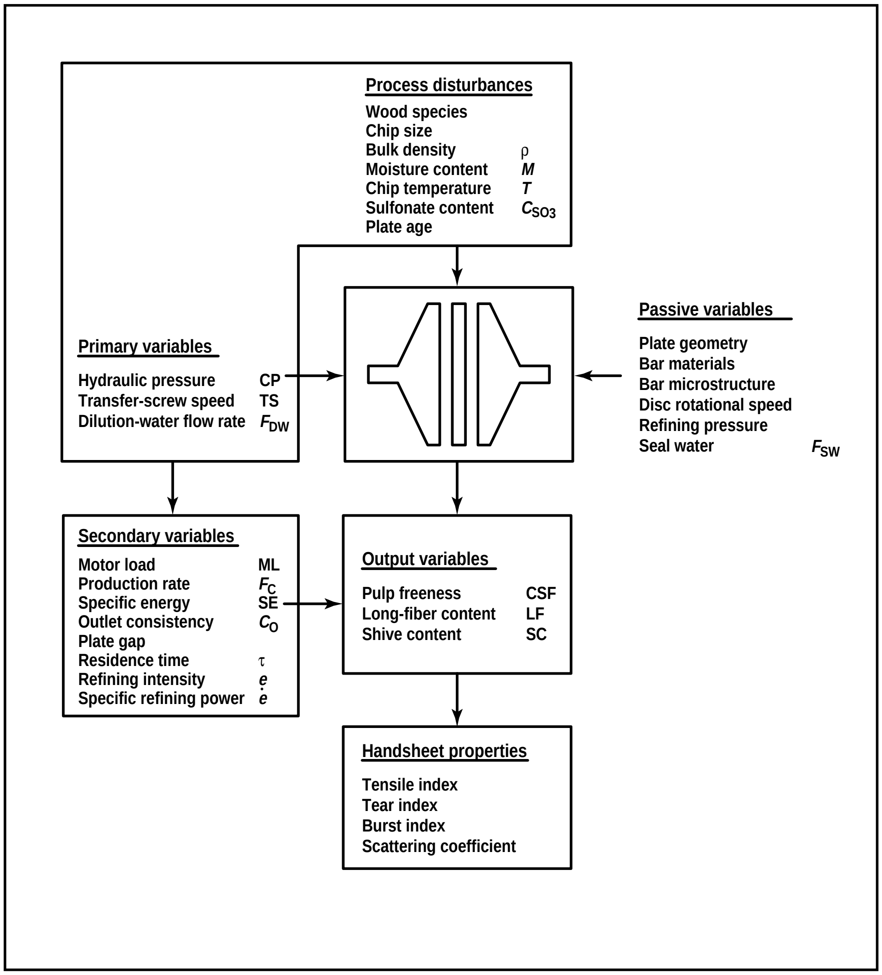
$$F_C = k_1 \rho \, TS \quad (1)$$

Variables for this and all following equations are defined in the Nomenclature section at the end of this paper.

Motor load

Studies have shown that the refiner motor load is a variable that depends mainly on the axial thrust applied to the refiner plates, the production rate, and the inlet consistency *(1, 2)*. Because of the complexity of the refining process, few works have studied the quantitative relationship

2. Variables in a refining system



between the closing pressure, production rate, and motor load. For a hydraulic loading system, we propose that there is a linear and additive effect of closing pressure, CP, and production rate, F_C, on the motor load, ML.

$$ML = k_2CP + k_3F_C \qquad (2)$$

Inlet and outlet consistency

The inlet consistency is dependent on the production rate, chip moisture content, dilution flow rate, and seal-water flow rate. The outlet consistency, c_O, can be calculated from mass and energy balances in the refiner.

$$c_O = F_C/(F_{WO} + F_C) \qquad (3)$$

where

$$F_{WO} = F_{WI} + F_{DW} + F_{SW} - F_S \qquad (4)$$

See Equations at end of paper (5)

$$F_{WI} = [M/(1–M)]F_C \qquad (6)$$

Specific energy and refining intensity

The specific energy, SE, is defined as the ratio of motor load to production rate.

$$SE = ML/F_C \qquad (7)$$

Many mills still use specific energy to control the pulp freeness, although this practice is now recognized to be insufficient. Most people agree that at least two variables are required to control the pulp properties, because the way in which the total energy is applied has a substantial effect on pulp quality.

How the energy is applied is measured by the refining intensity, e, which Miles *(3)* defines as the specific energy per bar impact. The average specific energy per bar impact, or refining intensity, is given by Eq. 8.

$$e = SE/N \qquad (8)$$

where N is the total number of impacts, which is proportional to the residence time, and is given by Eq. 9.

$$N = n\ h\ \omega\ [(r_1 + r_2)/2]\ \tau \qquad (9)$$

The symbol τ is the residence time of materials in the refiner. A simplified equation for calculating the residence time has been developed by Miles *(4)* and is given here as Eq. 10.

See Equations at end of paper (10)

Since wood is a viscoelastic material, its properties depend not only on the amount of energy absorbed at an impact, but also on the rate at which this energy is transferred. To describe this energy-transfer rate, Miles *(3)* introduced the concept of specific refining power, as defined in Eq. 11.

$$\dot{e} = SE/\tau \qquad (11)$$

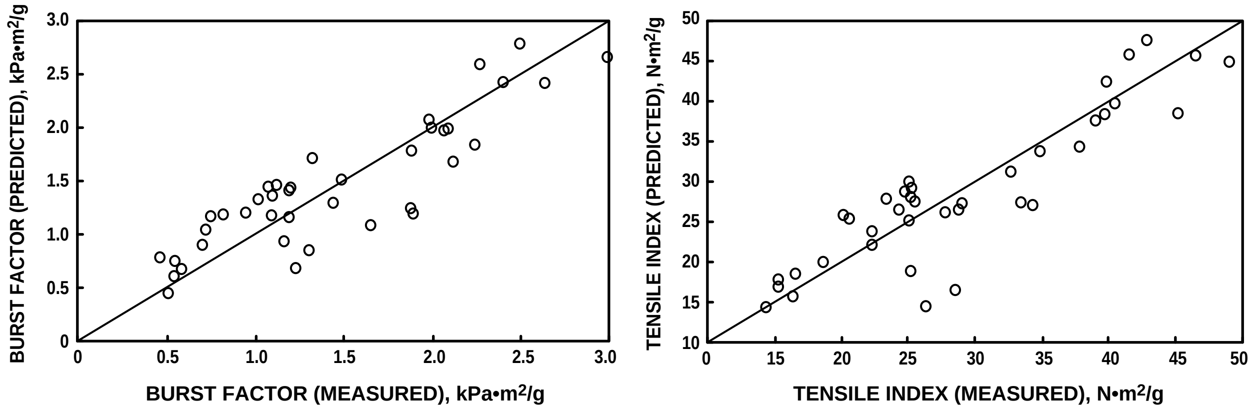
From the specific energy, the refining intensity, and the specific refining power, it is possible to predict such pulp properties as freeness, long-fiber content, and shive content.

Pulp properties

Experimental data have shown a good linear relationship between the logarithm of freeness and refining intensity at constant specific energy *(3)*. Strand and Mokvist *(2)* also observed that there was a good correlation between specific energy and freeness. The model presented here also includes the effect of sulfonate content on pulp properties.

At a constant specific energy, the effect of sulfonate content on freeness depends on the degree of sulfonation *(5)*. For a low degree of sulfonation (0–1.8%), freeness increases with sulfonate content, while

3. Correlation between predicted and measured values of burst strength (left) and tensile index (right)



I. Refiner operating conditions and nominal values of the variables

Variable	*Symbol*	*Primary refiner*	*Secondary refiner*
Production rate, tons/day	F_C	325	325
Chip bulk density, kg/m^3	[RHO]	100	...
Chip moisture content, %	*M*	50	...
Dilution flow rate, L/min	F_{DW}	300	108
Motor load, MW	ML	12.5	9.2
Closing pressure, psi	CP	1200	900
Pulp freeness, mL CSF	CSF_0	480	140
Long-fiber content, %	LF_0	67	55
Shive content, %	SC_0	1.8	0.4

II. Parameters k_1 through k_{13}

Parameter	*Value*	*Source*
k_1	1.2×10^{-3}	Mill data
k_2	10.4	Mill data
k_3	1562.5	Mill data
k_4	0.106	Ref. *(2)*
k_5	0.114	Ref. *(3)*
k_6	191	Ref. *(5)*
k_7	2.10	Ref. *(3)*
k_8	4.0×10^{-3}	Ref. *(3)*
k_9	9.6	Ref. *(7)*
k_{10}	4.26×10^{-3}	Ref. *(3)*
k_{11}	0.056	Ref. *(3)*
k_{12}	0.2	Ref. *(7)*
k_{13}	7.0	Ref. *(8)*

for a high degree of sulfonation (>1.8%), freeness decreases with the increasing sulfonate content. The sulfonate content in the CTMP process is generally below 0.8%, so freeness increases with sulfonate content for CTMP.

The combined effect of refining intensity, specific energy, and sulfonate content, C_{SO_3}, on pulp freeness can be described by Eq. 12.

$$CSF = \{[CSF_0 - k_4(SE - SE_0)] \times 10^{-k_5(e - e_0)}\} + k_6 C_{SO_3} \quad (12)$$

where CSF_0, SE_0, and e_0 correspond to a nominal operation point and depend on the refining process and the raw-material characteristics. C_{SO_3} is the sulfonate content of wood and is expressed as a percentage of oven dry (o.d.) wood.

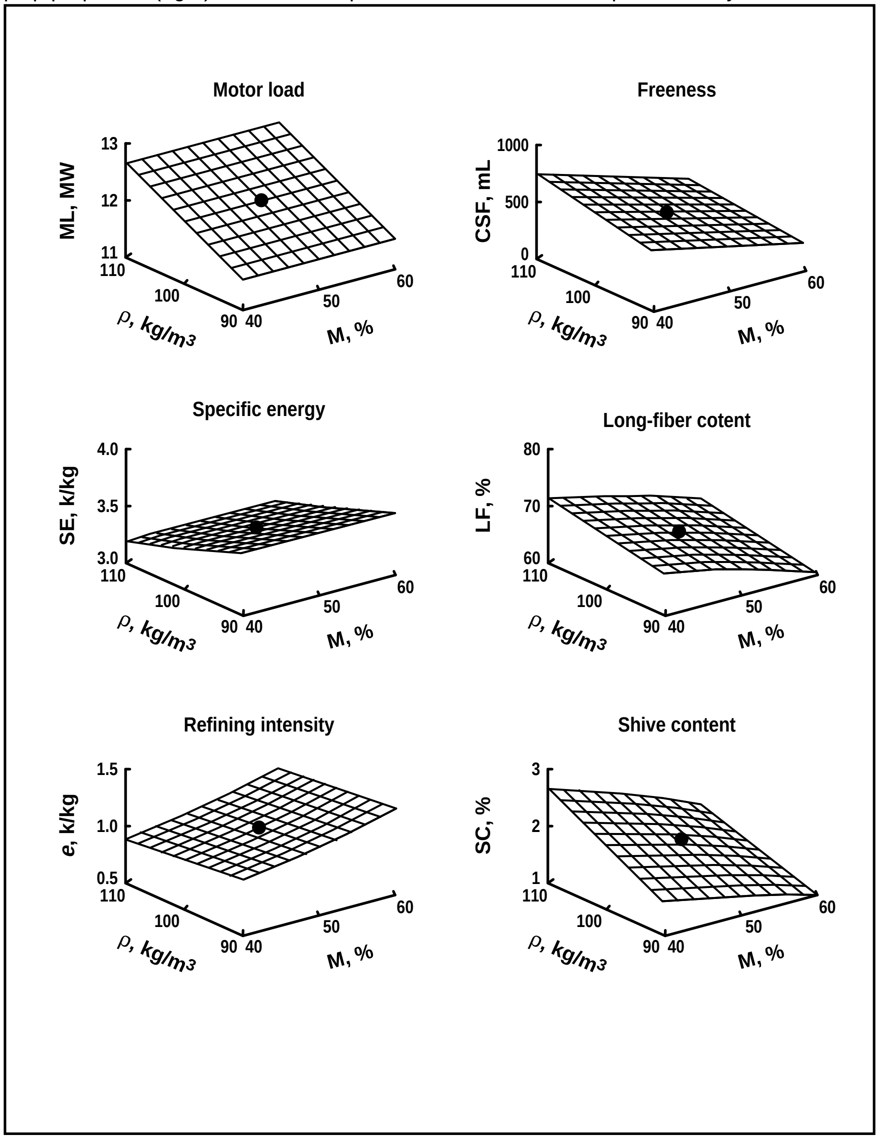
The long-fiber content, defined as the percent weight of the fibers retained on a 48-mesh screen *(6)*, seems to be linearly related to the specific refining power at a constant specific energy *(3)*. At the same time, for a given specific refining power, the long-fiber content decreases as the specific energy increases. Ferritsius and Moldenius *(7)* reported that the long-fiber content and the sulfonate content have a simple relationship when the pulp is refined to a constant freeness level. The combined effect can be described by Eq. 13.

$$LF = LF_0 - k_7(\dot{e} - \dot{e}_0) - k_8(SE - SE_0) + k_9 C^{SO_3} \quad (13)$$

where LF_0, SE_0, and $\dot{e}_0$ are the nominal values of long-fiber content, specific energy, and specific refining power.

The logarithm of the shive content has been found to be linearly related to the specific refining power at a constant specific energy *(3)*. Similarly, at a constant specific refining power, the shive content de-

4. Effect of chip bulk density and moisture content on refiner operating conditions (left) and pulp properties (right). The nominal point for each variable is represented by a filled dot.



creases logarithmically with increasing specific energy. In addition, Ferritsius and Moldenius *(7)* reported that the shive content is an exponential function of sulfonate content, as seen in Eq. 14.

See Equations at end of paper (14)

where SC_0 is a nominal value of shive content.

Yield

Atack *et al. (8)* found that sulfonation of eastern black spruce is accompanied by a loss of about 0.7% yield for every 0.1% increase in sulfonate content. In our simulations, we also assume that the yield loss is linearly related to the sulfonate content by Eq. 15.

$$\text{Yield} = 100 - k_{13} C_{SO_3} \qquad (15)$$

where k_{13} is a coefficient depending on the wood species. For eastern black spruce, it is 7.0.

Handsheet properties

Many researchers have discussed the classification of fibers to characterize mechanical pulps *(6, 9, 10)*. Multiple linear-regression techniques have been widely used to relate handsheet properties to mechanical pulp properties under specific conditions *(11, 12)*. However, the multiple linear-regression techniques are insufficient to handle large sets of independent variables.

The principal-component analysis technique *(13)* is an effective method of identifying the most important variables. Using the principal-component analysis technique, we found that freeness, long-fiber content, and shive content are the three most important pulp properties influencing handsheet properties, and these can be used to predict handsheet properties fairly well. A set of equations was established to predict tensile index, burst index, tear index, and specific light-scattering coefficient of handsheets prepared without removing the shives.

$$\text{Tensile} = 26.3 - 0.033\ \text{CSF} + 0.227\ \text{LF} - 2.13 \ln(1+\text{SC}) \qquad (16)$$

$$\text{Tear} = 1.91 + 0.021\ \text{CSF} + 0.077\ \text{LF} - 7.9 \times 10^{-5}(\text{LF})^2 \qquad (17)$$

$$\text{Burst} = 2.05 - 0.004\ \text{CSF} + 0.023\ \text{LF} + 0.05\ \text{SC} \qquad (18)$$

$$\text{SLSC} = 649 - 0.205\ \text{CSF} - 17.1 \ln(1+\text{SC}) \qquad (19)$$

Figure 3 shows the correlation between published data for burst index and tensile index *(14)* and the model predictions.

Simulations and discussions

The simulations were performed for a 325-ton/day CTMP production line in a pulp mill located in British Columbia, Canada. Twin refiners are used for both the primary and secondary stages. The operating conditions of the refiners and the nominal values of the variables are listed in **Table I**. The values k_1 through k_{13} for a given mill are dependent on either refiner characteristics or the operating conditions. The values used in our simulation are shown in **Table II**.

The simulation results presented in the following paragraphs apply to that particular production line, but they should be fairly representative as far as trends are concerned. Although the model can be used to simulate the effect of all the variables included in the model, we present only a few scenarios in the following sections.

Effects of chip bulk density and moisture content on operation of primary refiner

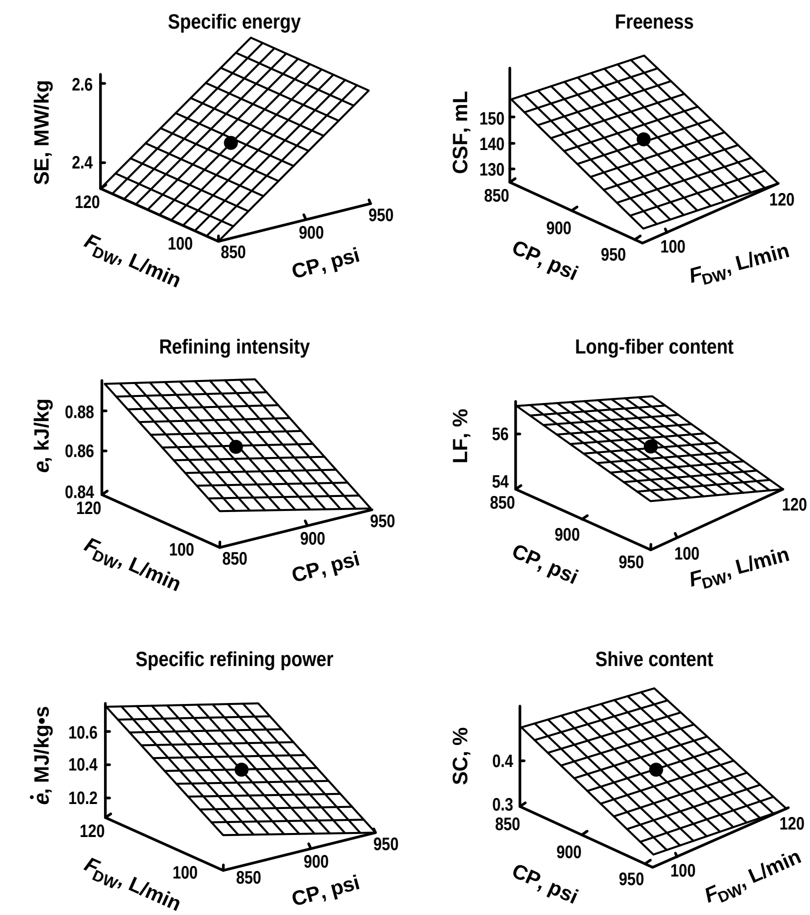
Chip bulk density and chip moisture content are the major disturbances affecting the operation of the primary refiner. **Figure 4** (left) shows the effects of these disturbances on the model's secondary operating variables (motor load, specific energy, refining intensity). The effects on pulp properties (freeness, long-fiber content, and shive content) are depicted in Fig. 4 (right).

When the transfer-screw speed, the closing pressure, and dilution flow rate are maintained at constant levels, an increase in chip bulk density is equivalent to an increase in the chip feed rate. This leads to an increase in motor load, as seen in Fig. 4. Although the motor load increases, the specific energy decreases, since the increase in motor load is outweighed by the increase in chip feed rate. Pulp freeness decreases when the bulk density is decreased or when the moisture is increased. The long-fiber content and shive content follow the same trend as freeness.

Effects of secondary-refiner closing pressure and dilution on pulp and handsheet properties

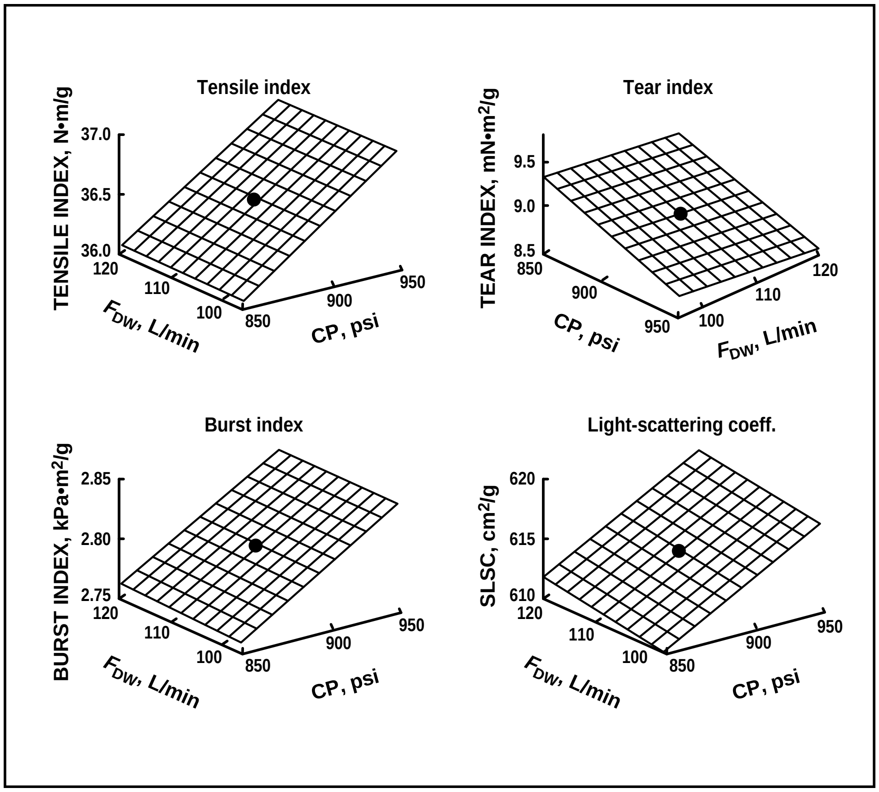
The material from the primary refiner is discharged to the primary cyclone, where steam is separated from the pulp. Assuming no fiber loss in the cyclone, the feed rate to the secondary refiner can be calculated from the primary refiner feed rate and the yield resulting from the sulfonation. The operating variables for the secondary refiner are then the dilution flow rate and the hydraulic closing pressure.

5. Effect of dilution flow rate and closing pressure of secondary refiner on operating conditions (left) and pulp properties (right). The nominal point for each variable is represented by a filled dot.



The refiner specific energy, refining intensity, and specific refining power vs. the dilution flow rate and closing pressure are shown in **Fig. 5** (left). Higher closing pressure leads to a longer residence time, which reduces the refining intensity. The simulation results for pulp prop-

6. Effect of dilution flow rate and closing pressure of secondary refiner on handsheet properties. The nominal point for each variable is represented by a filled dot.



Equations

$$F_{WO} =$$

$$\left(\{[(1-\varepsilon)\ \eta\ \mathrm{ML}]-[F_{WI}\ C_W(T_O-T_I)]\}\ [H_S-(C_W T_O)]\right)$$

$$-\left(\{[F_C C_C(T_O-T_I)]-[(F_{DW}+F_{SW})C_W(T_O-T_I)]\}/[H_S-(C_W T_O)]\right) \quad (5)$$

$$\tau = (\mu_R/\mu_T)$$

$$\left[(a\ \mathrm{SE}\ c_I\ L_S)/\left(\omega^3\ \{[L_S(r_2^2-r_1^2)]+(c_I\ \mathrm{SE}\ r_1^2)\}\right)\right]$$

$$\left(\ln(r_2/r_1)-0.5\ \ln\{[(L_S-c_I)\mathrm{SE}]/L_S\}\right) \quad (10)$$

$$\mathrm{SC} = \left(\mathrm{SC}_0 \times 10^{-\left[k_{10}\left(\mathrm{SE}-\mathrm{SE}_0\right)+k_{11}\left(\dot{e}\dot{e}_0\right)\right]}\right) e^{-k_{12} C_{SO_3}} \quad (14)$$

erties vs. the closing pressure and dilution flow rate are also shown in Fig. 5 (right). An increase in the closing pressure or a decrease in the dilution flow rate results in a decrease in the refining intensity and the average refining power. Lower refining intensity is beneficial to the fiber development. Increasing the closing pressure lowers freeness, long-fiber content, and shive content.

The handsheet properties corresponding to different closing pressure and dilution flow rates are shown in **Fig. 6**. It is apparent that the dilution flow rate has little effect on the tensile index, burst index, and specific light-scattering coefficient. While it has been suggested that pulp properties can be modified by varying the refining consistency, we have found that the practical range of operation is limited with industrial refiners. Decreasing the dilution flow rate will reduce the pulp brightness, while increasing the dilution water over a critical value could lead to plate clashing. Nevertheless, the dilution flow rate can be used to slightly modify the pulp properties, especially the tear index, as seen in Fig. 6.

The simulation results indicate that closing pressure is the most important variable in controlling tensile index, burst index, and specific light-scattering coefficient. Variation in production rate—either by manipulating the transfer-screw feeder speed or because of variations in chip bulk density—will produce large variations in pulp and handsheet properties.

Summary

The mathematical model presented in this paper relates the primary manipulated variables of refiners—transfer-screw feeder speed (production rate), closing pressure (specific energy), and dilution flow rate (consistency)—to pulp properties (freeness, long-fiber content, and shive content) and handsheet properties (burst, tensile, tear, and specific light-scattering coefficient).

The refining mechanism is represented by the refining intensity and the specific refining power. These two variables are calculated from the pulp residence time between the refiner plates, the number of impacts, and the specific energy, all of which depend on the refiner design and operating conditions.

The model can be used to predict the trend of the effects of operating variables on pulp and handsheet

Nomenclature

a	= 4 for a single disc refiner, 2 for a double disc refiner
c_I	= inlet consistency, %
c_O	= outlet consistency, %
C_C	= specific heat of wood chip, kJ/kg °K
C_W	= specific heat of water, kJ/kg °K
C_{SO3}	= sulfonate content, % on o.d. wood
CSF	= Canadian standard freeness, mL
CSF_0	= nominal value of CSF, mL
CP	= closing pressure, psi
e	= refining intensity, kJ/kg
e_0	= nominal value of refining intensity, kJ/kg
$\dot{e}$	= specific refining power, kJ/kg·s
$\dot{e}_0$	= nominal value of specific refining power, kJ/kg·s
F_C	= chip flow rate, kg/s
F_{DW}	= dilution flow rate, kg/s
F_{SW}	= seal-water flow rate, kg/s
F_{WI}	= water in the chips to the refiner, kg/s
F_{WO}	= water in the refiner discharge, kg/s
F_S	= steam flow rate out of refiner, kg/s
h	= 1 for a single disc refiner, 2 for a double disc refiner
H_S	= enthalpy of steam, kJ/kg
k_{1-13}	= constant parameters (must be obtained from mill data for each particular production line)
L_S	= latent heat of steam, kJ/kg
LF	= long-fiber content, %
LF_0	= nominal value of long-fiber content, %
M	= chip moisture content, %
ML	= refiner motor load, kW
n	= number of bars per unit length of arc of a refiner disc
N	= total number of impacts
r_1, r_2	= inlet and outlet radius of plate's refining zone, m
SE	= specific energy, kJ/kg
SE_0	= nominal value of specific energy, kJ/kg
SC	= shive content, %
SC_0	= nominal value of shive content, %
T_I, T_O	= inlet and outlet temperatures of the refiner, °C
TS	= transfer-screw feeder speed, rpm
ε	= heat loss of the refiner, %
η	= motor efficiency
μ_R, μ_T	= radial and tangential friction coefficient between pulp and discs
ρ	= chip bulk density, kg/m^3
τ	= residence time in refiner, s
ω	= refiner rotational speed, radians/s

properties. The simulated results presented here are based on a 325-ton/day CTMP production line. If this model is to be applied to a different refining process, the model parameters and the nominal values will have to be adjusted to reflect the conditions for that particular refining process and the characteristics of the raw materials. TJ

Literature cited

1. Miles, K. and May, W., *J. Pulp Paper Sci.* 16(2): J63(1990).
2. Strand, B. and Mokvist, A., *J. Pulp Paper Sci.* 15(3): 100(1989).
3. Miles, K. B., *Paperi Puu* 72(5): 508(1990).
4. Miles, K., *Paperi Puu* 73(9): 852(1991).
5. Atack, D., Heitner, C., and Karnas, A., *Pulp Paper Can.* 82(C): T103(1981).
6. Forgacs, O., *Pulp Paper Mag. Can.* 64(C): T89(1963).
7. Ferritsius, O. and Moldenius, S., "The effect of impregnation method on CTMP properties," *1985 International Mechanical Pulping Conference Proceedings*, EuCePa, Paris, pp. 91–100.
8. Atack, D. and Heitner, C., *CPPA Trans. Tech. Sect.* 5(4): TR99(1979).
9. Manstrom, B., *Papper och Tra.* 49(4a): 137(1967).
10. Brecht, W. and Klemm, K., *Pulp Paper Mag. Can.* 54(1): 72(1953).
11. Garceau, J. and Jones, H., *CPPA Trans. Tech. Sect.* 1(1): 28(1975).
12. Venkatesh, V., "A systems engineering approach to effluent control, pulp characterization and process design in mechanical pulp mills," Ph.D. thesis, University of Idaho, Moscow, 1976.
13. Kosanovich, K. A. and Piovoso, M. J., "Process data analysis using multivariate statistical methods," *1991 American Control Conference Proceedings*, American Automatic Control Council, Green Valley, AZ, p. 721.
14. Strand, B., "Simulation, control and online optimization on mechanical pulping systems," Ph.D. thesis, University of Idaho, Moscow, 1989.

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