Model-based optimization of Kamyr digester operation

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ABSTRACT: In the Kamyr digester used for kraft pulping processes, there are strong interactions between the many process variables, long time delays, and frequent disturbances in the operation. Steady-state operation is, therefore, difficult to obtain. A complex kinetics-diffusion, simulation model developed for the Kamyr digester operation was coupled with a continuous dynamic programming algorithm to find the optimum of a continuous, multivariable, nonlinear yield function subject to constraints. The optimization program was used to (a) determine an optimal set of operating conditions that would maximize pulp yield at a specific chip meter speed and blow-line kappa number and (b) determine optimal profile changes in effective alkali concentration and upper and lower heater outlet temperatures to minimize the amount of off-specification pulp produced during swings between types of wood. In the model pulp yield can be increased by about 5% on a relative basis by careful choice of operating conditions. In addition, significant reduction in the amount of off-specification pulp produced during swings has been achieved using optimal profile changes.

KEYWORDS: Algorithms, automatic control, continuous digesters, kraft pulping, machine design, models, optimization, variables.

Optimization and computer control of commercial kraft pulp digesters have been hindered for the following reasons:

- **Chip quality variations.** There are numerous chip characteristics that vary during daily operations. These variations cause two types of problems: nontarget cooking conditions and operational problems.
- **Measurement problems.** There has been a lack of instruments to analyze liquors and chip and pulp characteristics; more conventional measurements at the chip level are also well known.
- **Long process delays.** Changes may have been made during a previous shift, and the results are not observed until the following one. Delays cannot be eliminated by the control system, but good controls can minimize them.
- **Strong interactions between the process variables.**
- **Expense and difficulty of running experiments with production units.**

Several authors, however, have performed optimization studies with laboratory digesters *(1–3)*. The typical strategy is to run a large number of experiments and generate a response surface with respect to the necessary variables. The optimal operating conditions are then determined by interpolation between discrete points on the surface. Disadvantages of this approach are as follows:

- Generation of an accurate response surface requires many time-consuming and expensive experiments.
- The range of conditions that can be covered is limited by the ex-

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perimental equipment used; the optimum may be beyond the allowable range.

- It can be difficult to predict mill-scale operation from laboratory experiments.

Gustafson *et al. (4)* used a general mathematical model of the kraft pulping process that has been developed earlier *(5)* to generate the response surface. The primary advantages of this approach are that such experiments can be performed quickly with a computer, and the range of operating conditions is essentially limitless. Gustafson's model *(5),* however, does not simulate the digester's operation during disturbances that are caused by varying the chip species entered at the top of the digester.

The Purdue model of the Kamyr digester *(6–9)* is the most complex model of its type. It correlates, with experimental accuracy, all available laboratory and industrial data for pulping conditions that closely approximate those of commercial importance. This includes pseudo-steady-state hardwood and softwood swings.

The objective of the present investigation is to use the Purdue model for the kraft pulping process to achieve two goals:

- To determine the optimal set of operating conditions that would maximize, at a certain blow-line kappa number, an objective yield function at steady-state conditions
- To determine the optimal profiles for changing effective alkali and upper and lower heater temperatures to minimize the amount of off-specification pulp produced during a swing.

I. Operating variables for the base case and the optimal set

Operating variable	*Base case value*	*Optimal value*
Chip meter speed, rpm	13.0	13.0
White liquor NaOH concentration, lb NaOH/ft^3	6.2	6.4
White liquor Na_2S concentration, lb as NaOH/ft^3	2.0	2.1
Upper heater outlet temperature, °F	310.0	330.0
Lower heater outlet temperature, °F	330.0	360.5
White liquor flow rate, ft^3/h	3,180	2,200
Input black liquor flow rate, ft^3/h	720.0	540.0
White liquor temperature, °F	234.8	234.8
Input black liquor temperature, °F	190.0	190.0
Upper heater circulation flow rate, ft^3/h	12,000	12,000
Lower heater circulation flow rate, ft^3/h	12,000	12,000
Quench circulation flow rate, ft^3/h	0	0
Wash heater flow rate, ft^3/h	660.0	660.0
Wash heater outlet temperature, °F	190.9	190.9
Extraction flow rate, ft^3/h	6,747.9	6,747.9
Chip moisture, lb water/lb wood	0.55	0.55
Kappa number	31	31
Yield, lb/lb o.d. wood	0.4069	0.4270

Description of optimization method

We have coupled the Purdue model *(6-9)* with an optimum-search algorithm, DYNAM *(10),* in a single computer program. The Purdue model predicts a priori, among other things, lignin content, carbohydrate content, and effective alkali concentration within pulp chips as a function of time. Yield and kappa number are calculated at any time or height from the digester top during the cook.

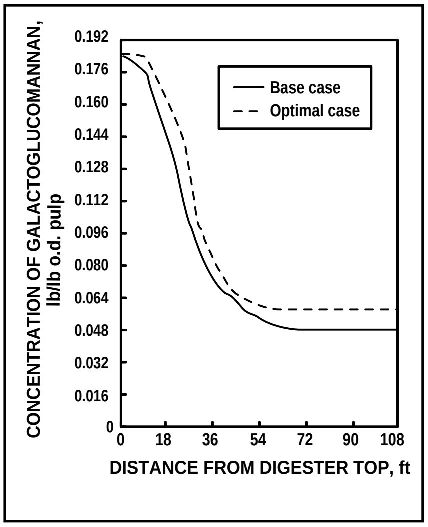
The DYNAM procedure is based on the "principle of optimality" stated by Cooper *(11).* This principle relates the properties of decisions made in sequence. Whatever the initial decisions are, the remaining decisions result in an optimum with regard to the first. This idea of sequencing decisions enables a complex problem of many decisions, or variables, to be broken down into a sequence of smaller problems with only a few variables. Each smaller problem is termed a stage, with its optimal decisions resulting in a "return" to the overall system objective function. This method of structuring sequential stages has proven effective in solving large problems of many variables.

The DYNAM algorithm and the pulping simulator work together as follows. A base case of pulping conditions, which closely approximates those of commercial importance, is chosen. Given these conditions and a set of constraints on operating variables, the simulator then calculates the value of the "objective function," i.e., the goal of the optimization procedure. This is a well-defined quantity, such as pulp yield. Once the initial value of the objective function has been determined, the DYNAM algorithm evaluates new pulping conditions, gradually moving toward the desired maximum or minimum in the objective function. It should be noted, however, that since this is a multivariable constrained optimization

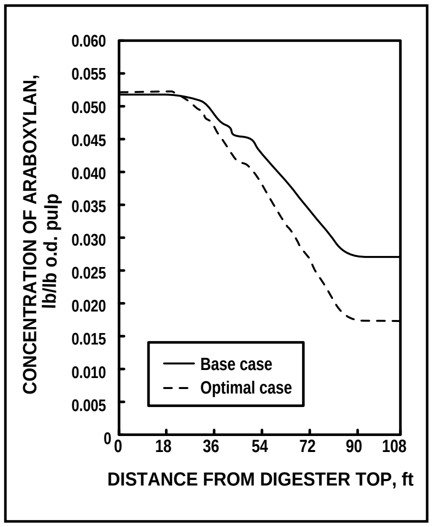
II. The composition of initial wood, base case, and optimal case blow-line pulp

Component	*Initial wood, lb/lb o.d. wood*	*Base case, lb/ lb o.d. pulp*	*Optimal case, lb/lb o.d. pulp*
Extractives	0.0698	0	0
High-reactivity lignin	0.0544	0.0015	0.0191
Low-reactivity lignin	0.2200	0.0178	0.0012
Cellulose	0.4180	0.3110	0.3310
Galactoglucomannan	0.1858	0.0479	0.0575
Araboxylan	0.0520	0.0286	0.0182

1. Concentration profile of galactoglucomannan



2. Concentration profile of araboxylan



technique, the constrained optimum obtained (e.g., optimal pulp yield) is not an absolute optimum, because its value depends on the constraints specified for the operating variables.

Applications of model-based optimization

Maximization of pulp yield

We first used the coupled optimizer-simulator to determine the pulping conditions that would maximize the yield of a kappa no. 31 blow-line pulp; this is a typical commercial-value pulp. Yield is defined as the total mass of the five wood components (high- and low-reactivity lignins, cellulose, galactoglucomannan, and araboxylan) per unit mass of oven-dry (o.d.) wood. To minimize the number of operating variables involved, a model-based sensitivity analysis was performed *(12)*. For softwood, **Table I** shows the steady-state base case values of the operating variables and their optimal values obtained from the optimizer. Only six variables were involved in the optimization procedure: white liquor sodium hydroxide concentration, white liquor sodium sulfide concentration, upper heater outlet temperature, lower heater outlet temperature, white liquor flow rate, and input black liquor flow rate. All other variables were held constant at their base case values. The two sets of variables produced a kappa no. 31 blow-line pulp with the yield from the optimal set being about 5% higher, on a relative basis, than that of the base case set.

Note that optimization results reflect the idealized digester simulated by the pulping model. In the light of the model's assumptions, a discussion of the optimization results is given below.

Table II shows a comparison of the composition of initial wood, the base case, and the optimal case blowing pulp. In initial wood, an 80/20 ratio of low- to high-reactivity lignins is used *(13, 14)*. The rate of dissolution of wood components is expressed as follows[1]:

$$X_i = -(k_1 X_6 + k_2 X_6^{1/2} X_7^{1/2})\, X_i \qquad (1)$$

where

X_i = concentration of wood component *i* (lb/lb o.d. wood)

X_6 = concentration of entrapped hydroxl ions (lb NaOH/ft^3)

X_7 = concentration of entrapped hydrosulfide ions (lb as NaOH/ft^3).

k_1 and k_2 are reaction rate constants determined by the Arrhenius equation:

$$k = A \exp(-E/RT) \qquad (2)$$

where

A = frequency factor, lb/ft^3/h

E = activation energy, kcal

T = absolute temperature, °K

R = universal gas constant.

A closer investigation of the data in Table II indicates that overall solubilities of low-reactivity lignin and araboxylan have increased under the optimal case conditions compared to the base case conditions. Those of the high-reactivity lignin, cellulose, and galactoglucomannan have decreased.

Figures 1 and 2 show the concentration profiles for galactoglucomannan and araboxylan, respectively, for the optimal and base case conditions. A comparison of these figures indicates that the dis-

[1]The dissolution rate of wood components as expressed in Eq. 1 contains two reaction rate constants: k_1 (for soda pulping) and k_2 (for kraft pulping). For each reaction rate constant, there is a value for frequency factor, *A*, and activation energy, *E*.

solution rate of araboxylan is very low in the impregnation zone (the top 22.5 ft of the digester height) as compared to that of galactoglucomannan. Taking into consideration that 25% of the initial wood content of galactoglucomannan is unreactive *(15, 16)*, about 70% of reactive galactoglucomannan is dissolved in the impregnation zone at base case conditions compared to about 50% at optimal conditions. This could be explained by the lower optimal flow rates of white and black liquors fed into the digester top, as indicated in Table I. Figure 2, however, indicates that almost no araboxylan is dissolved in the impregnation zone, suggesting a relatively low sensitivity of the araboxylan dissolution rate to the caustic content of white and black liquors.

Araboxylan, however, almost completes its dissolution in the heating and cooking zone (at a height of 22.5–74.4 ft from the digester top), with more araboxylan dissolving at optimal conditions apparently due to the higher optimal temperatures. As has been shown for araboxylan *(9)*, and for an increase in lower heater outlet temperature from 330.0°F in the base case to 360.5°F in the optimal case, k_1 and k_2 increase by a factor of 2.1 and 5.6, respectively. On the other hand, for an increase in upper heater outlet temperature from 310.0°F in the base case to 330.0°F in the optimal case, k_1 and k_2 increase by a factor of 1.7 and 3.3, respectively. Therefore, Eq. 1 clearly shows that the effect of temperature on the rate of araboxylan dissolution is more significant than the effect of effective alkali charge. The effect of temperature on the dissolution rates of galactoglucomannan and araboxylan can be quantitatively assessed from values of frequency factors and activation energies *(9)*.

Considering Eq. 2, for galactoglucomannan:

$$A_1 = 1.725 \times 10^3, E_1 = 6, A_2 = 1.50 \times 10^4, E_2 = 9$$

and for araboxylan:

$$A_1 = 1.127 \times 10^7, E_1 = 17.50, A_2 = 6.325 \times 10^{19}, E_2 = 40.00.$$

Subscript 1 indicates the reaction rate constant for soda pulping, k_1, and subscript 2 indicates the reaction rate constant for kraft pulping, k_2, as expressed in Eq. 1.

For an increase of 25°F in heating zone temperature (the average temperature increase over the two heaters in the optimal set compared to the base case set), the reaction rate constant, k_2, of araboxylan increases to about four times that of galactoglucomannan over the same temperature range.

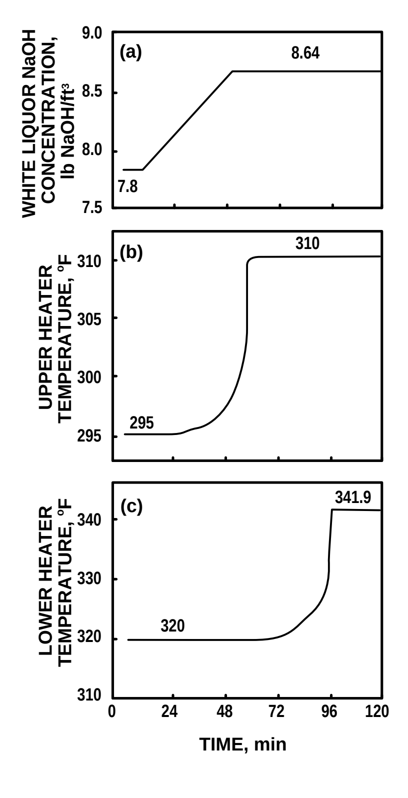
III. Chronology of events in the Kamyr digester, hours

Steady-state operation with hardwood	0–0.40
Swing to softwood	0.40
Interface of softwood-hardwood	
At top heater	0.74
At lower heater	1.00
Enters cooking zone	1.26
Enters quench zone	2.10
Enters wash zone	2.25
At blow-line	3.25
Steady-state operation with softwood	8.00–10.00
Swing to hardwood	10.00
Interface of hardwood-softwood	
At top heater	10.34
At lower heater	10.60
Enters cooking zone	10.86
Enters quench zone	11.70
Enters wash zone	11.85
At blow-line	12.85

Minimization of off-specification pulp produced during a swing

In commercial plants that frequently switch between hardwood and softwood chips, the chip feed rate is generally kept constant. To prevent overcooking the hardwood, somewhat milder conditions are then used (i.e., lower temperatures and/or less concentrated caustic solutions). Since the changes in operating conditions are often made rather abruptly, portions of the hardwood chips are cooked under conditions that are applicable to softwood chips and vice versa. Furthermore, the residence times of caustic solutions in the digester are generally not the same as those of the chips. Because

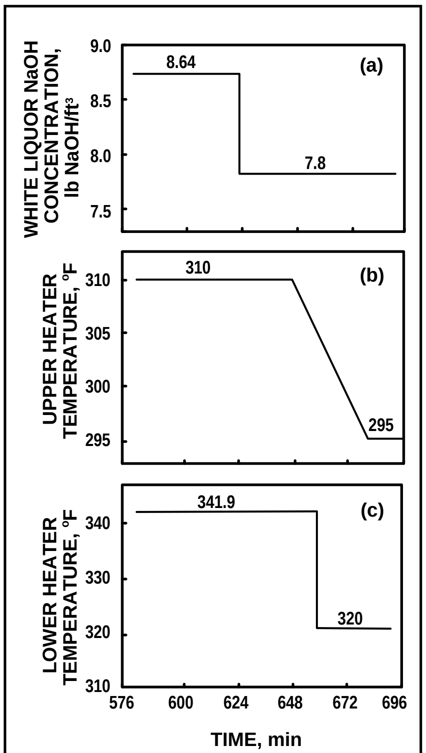
3. Optimal profiles for changing (a) white liquor NaOH concentration, (b) upper heater temperature, and (c) lower heater temperature during a swing from hardwood to softwood



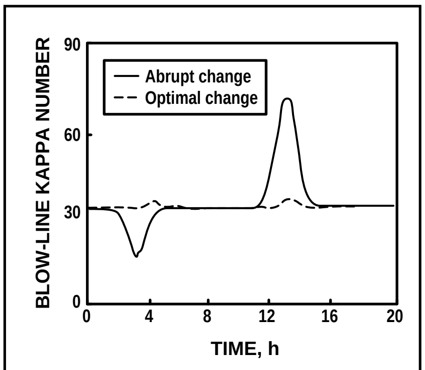
IV. Values of operating variables used for cooking hardwood and softwood at a chip meter speed of 18 rpm

Operating variable	*Hardwood*	*Softwood*
Chip meter speed, rpm	18.0	18.0
White liquor NaOH concentration, lb NaOH/ft^3	7.80	8.64
White liquor Na_2S concentration, lb as NaOH/ft^3	2.00	2.00
Upper heater outlet temperature, °F	295.0	310.0
Lower heater outlet temperature, °F	320.0	341.9
White liquor flow rate, ft^3/h	2,600	2,600
Black liquor flow rate, ft^3/h	520.0	520.0
White liquor temperature, °F	234.8	234.8
Black liquor temperature, °F	190.0	190.0
Upper heater circulation flow rate, ft^3/h	12,000	12,000
Lower heater circulation flow rate, ft^3/h	12,000	12,000
Quench circulation flow rate, ft^3/h	0	0
Wash heater flow rate, ft^3/h	660.0	660.0
Wash heater outlet temperature, °F	190.9	190.9
Extraction flow rate, ft^3/h	6,747.9	6,747.9
Chip moisture, lb water/lb wood	0.55	0.55

4. Optimal profiles for changing (a) white liquor NaOH concentration, (b) upper heater temperature, and (c) lower heater temperature during a swing from softwood to hardwood



5. Blow-line kappa number during 20 hours of digester operation with (a) abrupt change of operating conditions at same time as swings and (b) optimal change of operating conditions



of these problems in coordinating operating condition changes, most mills produce significant amounts of off-specification products during or just following a switch. It is economically important to minimize this product that is frequently referred to as twilight pulp.

The Purdue model *(6–9)* divides the Kamyr digester into 50 horizontal sections, one on top of the other, with the assumption that perfect mixing occurs in each section, resulting in uniform compositions and temperatures throughout each section. The type of wood and conditions in each section can be determined. Thus, appropriate rate constants and operating conditions can be determined and applied for each section. The optimizer, in this case, minimizes a function related to the amount of off-specification pulp produced during a swing by making appropriate changes in three variables: white liquor sodium hydroxide concentration and upper and lower heater temperatures.

Table III shows the chronology of events during the simulation of steady-state operation and the swings first from hardwood to softwood, and later softwood to hardwood, at a chip meter speed of 18 rpm. Steady-state operation for hardwood pulping occurred from 0 to 0.4 hours. At 0.4 hours, an abrupt change from hardwood to softwood was made. Computer calculations indicated that steady-state pulping of the softwood occurred within 7–8 hours. At 10 hours, an abrupt change was made to hardwood. Table III also indicates the location of the hardwood-softwood interface along the digester.

Table IV shows the operating conditions that produce a kappa number of 31 for both hardwood and softwood at a chip meter speed of 18 rpm. These operating conditions provided the most severe conditions for the swings.

Figure 3 shows the optimal profiles for changing white liquor sodium hydroxide concentration and upper and lower heater outlet temperatures to minimize the amount of off-specification pulp during a swing from hardwood to softwood; **Fig. 4** shows those optimal profiles for the change from softwood to hardwood. For the upper heater temperature optimal profile in Fig. 3, the profile equation covering times from 24 min (the time of the swing to softwood) to 56 min is:

$$Y = 295 + 0.78X - 8.2 \times 10^{-2}X^2 + 2.1 \times 10^{-3}X^3 \quad (3)$$

For the lower heater temperature optimal profile in Fig. 3, the profile equation for times between 72 and 96 min is:

$$Y = 528 - 9.57X + 0.11X^2 \qquad (4)$$

In Eqs. 3 and 4, Y represents the temperature (°F) and X the distance (ft) of the hardwood-softwood or softwood-hardwood interface from the digester top. **Figure 5** shows the blow-line kappa number during 20 hours of digester operation with (a) an abrupt change of operating conditions at the same time as the swings and (b) optimal changes of operating conditions[2].

There is a significant reduction in the amount of off-specification pulp produced during the two swings. However, note that the assumption of an abrupt switch from one type of wood to another may be partly incorrect. Some companies randomly mix chips for 15–30 min after a switch is started. In addition, the model assumption of perfect mixing in each of the 50 digester sections results in some forward and backward mixing of the reactants.

[2]In Fig. 5, the blow-line kappa number of 31 for both softwoods and hardwoods results from running the digester under different operating conditions that are appropriate for each type of wood during the indicated 20 hours of operation. The switch from one set of operating conditions to another is done abruptly, with the switch from one type of wood to another in Case (a) and following the profiles shown in Figs. 3 and 4 in Case (b).

Conclusions

We have demonstrated the potential value of using an accurate kraft-pulping simulator coupled with an optimum-search algorithm to optimize pulping conditions. In two specific optimization studies, we obtained significant improvements over pulping in the conventional manner. Because the accuracy of the pulping simulator has been demonstrated over a wide range of operating conditions, including transients such as hardwood-softwood swings, the results obtained here suggest likely strategies for improvements in mill operations. TJ

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