A real-time, model-based expert system for multiple-effect evaporators

Todd R. Brooks and Louis L. Edwards

ABSTRACT: This is the first on-line expert system developed for multi-effect evaporators.

KEYWORDS: Computer programs, computers, development, evaporators, expert systems, information systems, mills (factories), models, operations, optimization, performance, process control, simulation, trouble shooting.

Black-liquor evaporation typically accounts for 25% of the total steam-heat requirements in a kraft pulp mill, making it the mill's largest single user of process steam (*1*). Multiple-effect evaporators can perform this task economically if they are adequately maintained and operated (*2*). On-line expert systems, also known as advisory systems, can provide more information about the operation of these energy-intensive processes than is normally available from traditional control equipment. A similar advisory system was recently developed for recovery boilers (*3*), but there are no published accounts describing an expert system for evaporators.

Process equations

Problems with liquor evaporation are best explained in terms of the combined convective/conductive heat-transfer equation that governs the process. The transfer of energy in each effect of the evaporator is represented by the following relationship:

$$q_n = U_n A_n \Delta T_n \qquad (1)$$

where

q_n = heat transferred

n = effect number

U_n = heat-transfer coefficient

A_n = heat-transfer area

ΔT_n = apparent temperature difference.

The apparent temperature difference in Eq. 1, ΔT_n, is the difference between the heating-steam temperature at saturation and the vapor-dome temperature in a given evaporator effect.

The overall temperature drop of the complete evaporator set is the difference between the saturated steam temperature in the first effect and the saturated vapor temperature in the last effect, less the boiling point rise of each effect.

$$\Delta T_T = T_{S1} - T_{VN} - \sum_{n=1}^{N} \mathrm{BPR}_n \qquad (2)$$

where

ΔT_T = overall temperature drop

T_{S1} = raw saturated steam temperature in first effect

N = number of effects

T_{VN} = saturated vapor temperature to condenser in last effect

BPR_n = boiling point rise in a given effect.

The total heat transferred, q_T, is calculated from the sum of the heat transferred in each effect. This is directly proportional to the evaporation rate and steam use.

$$q_T = \sum_{n=1}^{N} q_n \qquad (3)$$

Evaporator difficulty usually reveals itself as a problem with one or more of the terms in Eqs. 1—3. For example, a fouled condenser will not provide enough vacuum to the final effect, causing the vapor-dome temperature to increase. From Eqs. 1 and 3, it can be shown that the driving force of the last effect must decrease and, all else being equal, q_n and q_T will decrease. The result will be a drop in evaporation rate.

These relationships, used in conjunction with an expert system and evaporator model, are useful diagnostic tools and can help in developing strategies for operating evaporators more efficiently.

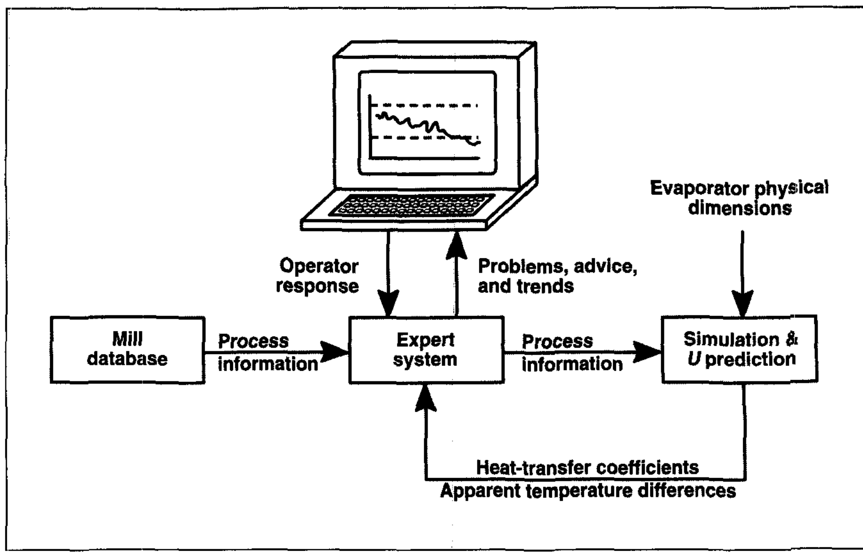
Brooks is a research associate and Edwards is a professor at the University of Idaho, Dept. of Chemical Engineering, Moscow, ID 83843-4199.

Overall system configuration

Figure 1 shows the relationship among the system components. The mill database, the RTAC expert-system shell (*4*), and the PCGEMS simulation model (*5*) reside on a single computer. The computer is a VAXstation 3100 with 16 megabytes RAM, and the operating system is VMS-DECwindows. The program runs in a windows environment, so it is relatively simple to customize for individual mills or reconfigure when changes are made. The "mill" database, for purposes of this research, consisted of a 36-h history of actual process information from a mill evaporator.

The expert system requests information from both the database and the simulator and executes predefined if–then rules to determine the status of the evaporator (e.g., low evaporation rate). The information requests are synchronized according to (a) when they are needed for rule execution, (b) when they are available, and (c) how long the information is considered to be accurate. If the system identifies a problem, it sends a message to the operator's terminal and provides advice.

1. Expert-system configuration



I. Comparison of actual and predicted temperature drops for a six-effect evaporator set

	Effect number					
	1	*2*	*3*	*4*	*5*	*6*
Actual temperature drop, °C	8	11	14	11	12	17
Predicted temperature drop, °C	9	11	11	12	12	17

Prediction of heat-transfer coefficient

Heat-transfer coefficients can be calculated iteratively if the vapor-dome temperatures for each effect are available on-line. When these temperatures are not directly accessible, the coefficients must be estimated by empirical correlations. Some of the techniques that are used to identify tube scale also require a predicted coefficient.

Two studies of heat transfer during black-liquor evaporation describe models for estimating these coefficients (*6, 7*). The Gudmundson model is computationally modest and has been successfully integrated into PCGEMS. The foundation of the Gudmundson model is a multivariable correlation of heat flux, feed rate, feed subcooling or superheating, liquid boiling point, and liquor dissolved-solids content. Heat flux is the most important of these because of the nonlinear relationship between heat flux and the temperature driving force in two-phase, buoyancy-driven flow. An additional aspect of the Gudmundson model is foaming and nonfoaming heat transfer. Foam in an evaporator effect results in a heat-transfer coefficient as high as twice the nonfoaming coefficient and can substantially change evaporator operation.

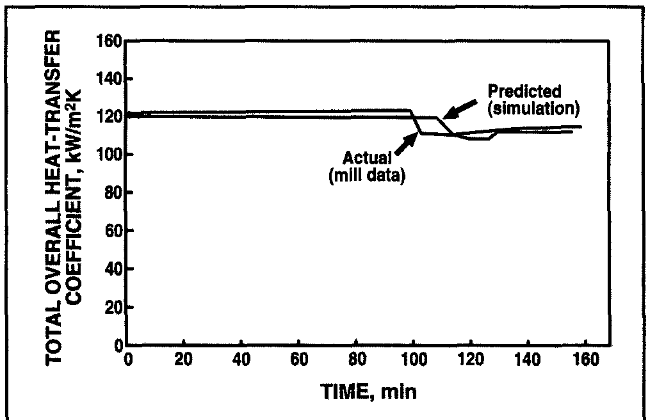
Model inputs and outputs

Input requirements for the simulation model are divided into two classes: equipment parameters and process variables.

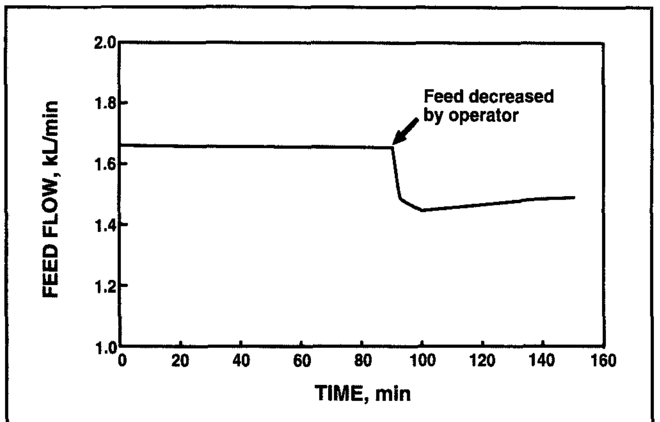
- Equipment parameters—heat-transfer area of each evaporator body, tube diameter, number of tubes, tube thermal conductivity, and estimated scale thickness, if any.
- Process variables—weak-black-liquor feed rate, dissolved solids, temperature, steam pressure, and concentrated black-liquor solids. All of these variables are normally available on a mill distributed-control system (DCS).

The outputs of the simulation are heat-transfer coefficients, boiling-point elevations, product dissolved solids, vapor-dome temperature, and apparent temperature difference in each effect.

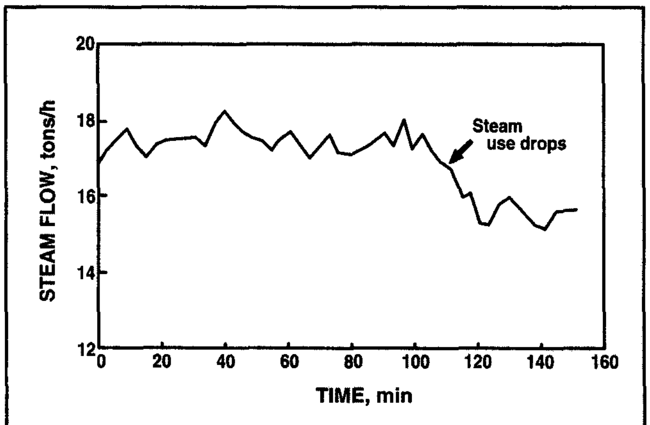
2. Comparison of actual and predicted heat-transfer coefficients



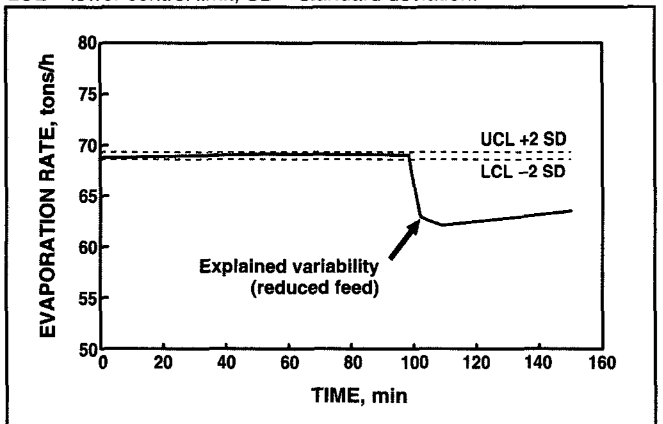
3. Weak black-liquor feed (mill data)



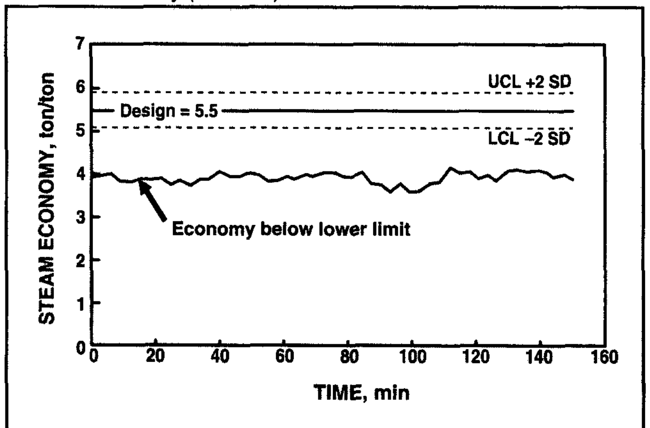
4. Steam flow to evaporator (mill data)



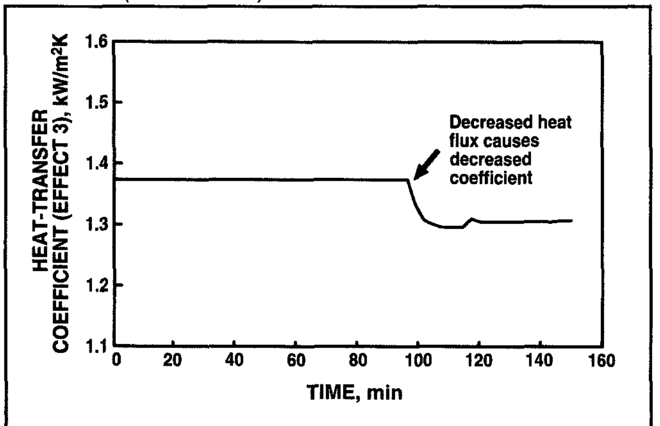
5. Evaporation rate of evaporator (mill data). UCL = upper control limit; LCL = lower control limit; SD = standard deviation.



6. Steam economy (mill data)



7. Predicted (Gudmundson) heat-transfer coefficient for Effect 3



Model validation

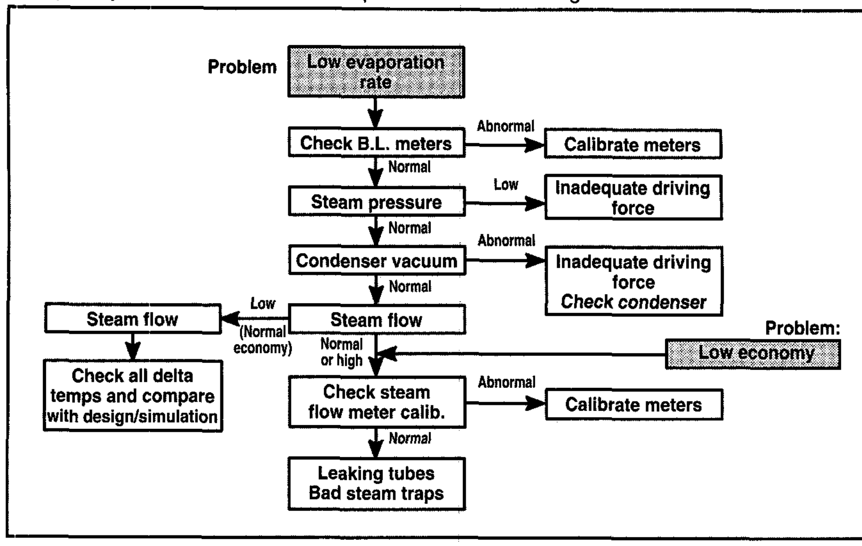
The simplest test of model accuracy is to observe the ratio of total heat transferred to the liquor and the overall temperature driving force and check this against the ratio calculated by the model. **Figure 2** shows these data for a 2.5-h run. This is referred to as a "total" overall heat-transfer coefficient to emphasize the fact that it represents the conditions around the entire evaporator set, not just around a single effect. The model tends to lag a bit behind the actual process because of the extra computer time required to recalculate the model during transient periods.

As further model validation, actual temperature drops are compared with predicted values in **Table I.** These data represent a "snapshot" of the evaporator at a specific point in time. The average error in prediction is 0.8°C, with the maximum deviation occurring at Effect 3 with a prediction error of 3°C.

Measured and predicted process trends

Trends of all process variables can be viewed through the system's graphical interface, which arranges on-screen data in an intuitive fashion. For example, apparent temperature differences, both predicted and measured, can be displayed at the same time. This adds an extra dimension to the system not found in a standard DCS, and it is possible to make a quick visual comparison of the measured and predicted temperature drops for a given effect. When the measured apparent temperature drop of one effect begins to increase relative to the predicted value, scaling is likely the problem. In such an instance, a message indicating the apparent problem and its source is sent to the operator terminal. Depending on the specific mill application, the "measured" heat-transfer coefficients can be similarly displayed for comparison with predicted values.

8. Expert-system decision tree for evaporator troubleshooting



Cause-and-effect relationship: U and evaporation rate

To illustrate the impact of various process variables on the heat-transfer coefficient, a 2.5-h run was performed, with the model estimating U (heat-transfer coefficient) every 3 min. **Figure 3** is a trend plot of the feed rate, which the operator decreased by 13% after 90 min. Both the steam flow (**Fig. 4**) and the evaporation rate (**Fig. 5**) drop because of the decreased feed flow and control of strong black-liquor solids. Pressure in the first and final effects remained steady, resulting in a constant ΔT_T. **Figure 6** shows that the steam economy also remained relatively constant. Since the steam flow rate was decreased with a nearly constant ΔT_T, q_T also decreased. As seen in **Fig. 7**, the predicted heat-transfer coefficient for Effect 3 drops because of the decreased q_T, illustrating the dependence of the heat-transfer coefficient on the evaporation rate. The decreased flow rate and resulting decreased velocity also contribute to the decrease of the heat-transfer coefficient. Heat-transfer coefficient for all the other evaporator effects dropped similarly. This is quantitative evidence of the mill observation that evaporators "run worse" at low evaporation rates.

Troubleshooting example

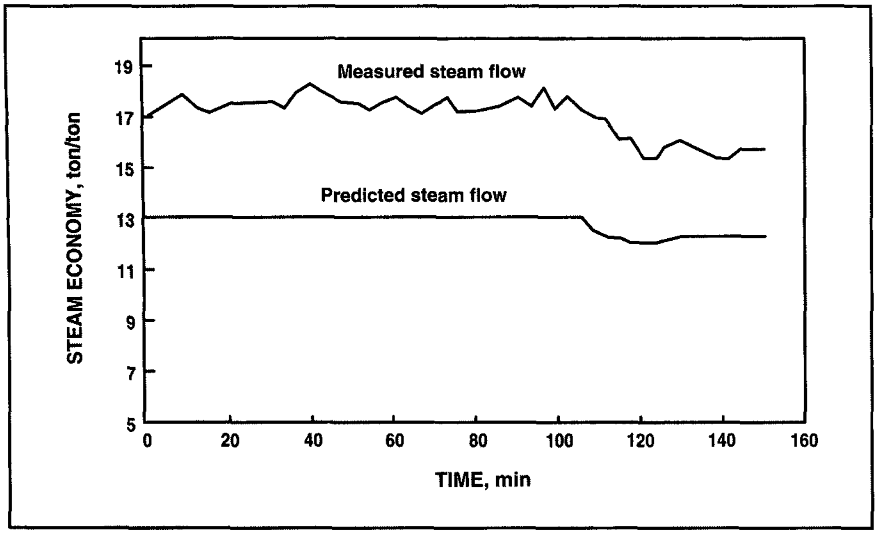
Low evaporation rate or low economy of a set is determined by violation of control limits. The limits are set at ± 2 standard deviations (± 2σ) from a nominal operating point. The causes of low economy or low evaporation rate can be diagnosed from a combination of available on-line sensors, simulation, and logical rules (*8*). **Figure** 8 shows the decision tree used by the expert system for troubleshooting.

Low evaporation rate

From Eqs. 1–3 it can be seen that low evaporation rate is a result of either a low ΔT_T or low U, since evaporation rate is directly proportional to q_T. Of course, it is also possible that reduced feed or a major upset such as a tube leak is causing the problem, but these can be deduced as well.

Once it is determined that evaporation rate is low and that reduced feed or incorrect feed meters are not the reason for the low rate, the steam pressure is checked. Low steam pressure indicates a low overall temperature driving force, ΔT_T, resulting in low q_T and poor evaporation rate. If the steam pressure is found to be normal, the vacuum at the final effect is measured. If this is low (i.e., high absolute pressure), then ΔT_T is low, resulting in the

9. Measured and predicted steam flows



poor evaporation rate. Low vacuum is usually traced to condenser fouling or an improperly functioning ejection system.

If steam use is low in proportion to the low evaporation rate (normal economy) and ΔT_T is normal, fouling of one or more of the effects is the cause. This can also be determined from a high apparent temperature difference, ΔT_n, in the offending effect.

Low economy

If the steam flow, which is also directly related to q_T, is abnormally high (corresponding to low economy), then either the flow meter is out of calibration or all the steam is not being used for evaporation. This can mean that steam is escaping directly into the black liquor through a leaking tube. It is also possible that the steam is passing directly into the condensate system through an open or faulty steam trap or orifice plate.

Real-time advice

The heuristic approach to problem solving is well adapted for computer applications. The decision tree in Fig. 8 has been programmed into the system as a series of if–then rules. Process conditions are continually checked against the rules, and text messages sent to the terminal identify any possible problems and the likely reasons. A graphical picture of the evaporator set is also displayed and contains a color-coded schematic that shows where the problem is located.

An effective expert system must be able to discriminate between real and apparent problems. For example, the evaporation rate of Fig. 5 appears to breach the lower control limit. In this case, however, the decreased feed is the cause, and there is no problem. If–then rules can easily filter out such occurrences.

Steam economy is, by definition, independent of evaporation rate. The normal steam economy for the evaporator whose data was used in this report is about 5.5 tons of water removed per ton of steam. Therefore, the steam economy of 4.0 tons/ton in Fig. 6 indicates a problem. Since the model has been validated against mill data and incorporates a rigorous material and energy balance, estimates of the amount of steam that should actually be used are credible. **Figure 9** shows this on-line prediction of steam use compared with the value measured at the mill. This abnormally high steam use, along with a low economy, suggests three possible causes: incorrectly calibrated steam flow meter, a faulty steam trap allowing steam to leak into the condensate system, or a leaking tube.

Conclusion and recommendations

Expert systems are useful tools for analyzing the operation of multi-effect evaporators. If the expert system is to operate in real time, it must have access to on-line sensor information such as steam pressure, steam flow, feed flow, feed temperature, and vapor-dome pressures. Simulation is an important aspect of the expert system and provides insight into the operation not normally available from standard control systems. The expert system also can help minimize evaporator downtime by identifying long-term trends and using these to schedule wash-outs and boil-outs. ■

Literature cited

1. Morrison, K. A. and Schroderus, S. K., Pulp Paper Can. 90(2): 83(1989).
2. Nystrom, E. W., Telford, C. D., and Murray, F. E., Pulp Paper Can. 87(8): 75(1986).
3. Smith, D. B., Edwards, L. L., and Damon, R. A., Tappi J. 74(11): 93(1991).
4. RTAC Engineer's Reference, Mitech Corp., Concord, MA, 1991.
5. Edwards, L. L., and Baldus, R. F., PCGEMS Documentation, Chemical Engineering Dept., University of Idaho, Moscow, ID, 1987.
6. Gudmundson, C., Svensk Papperstid. 75(22): 901(1972).
7. Olauson, L., Svensk Papperstid. 84(9): R61(1981).
8. Almond, C. B. Jr., Southern Pulp Paper 45(8): 30(1982).

This research was supported by James River Corp. Hardware was supplied by Digital Equipment Corp. and software provided by Mitech Corp. The authors wish to thank R. F. Baldus and D. B. Smith of James River Corp. and F. V. Matérn of ÅF-IPK AB for providing valuable data and information.

Received for review Dec. 6, 1991.

Accepted April 4, 1992.