

D₁₀₀-STAGE BLEACHING CONTROL WITH FUZZY LOGIC

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"FUZZINESS" TRIES TO DESCRIBE INACCURACIES AND UNCERTAINTIES THAT ARE COMMON IN EVERYDAY DISCUSSIONS BUT IMPOSSIBLE TO DEAL WITH USING MATHEMATICAL TOOLS. WHILE COMMON MATHEMATICS CANNOT DEAL WITH VARIABLES "A LITTLE BIT OVER NORMAL," FUZZY LOGIC CAN.

IN MODERN PULP MILLS THAT PRODUCE ELEMENTALLY chlorine-free (ECF) pulp, bleaching processes begin with a chlorine dioxide stage (if we do not count antecedent oxygen stages as regular bleaching stages). Most of the lignin, the outstanding color compound in pulp, is removed in the D₁₀₀ stage and the following alkaline stage. The lignin removed in this so-called prebleaching contributes to optimal chemical usage and yield in bleaching processes. Good control of the D₁₀₀ stage results in easier control and chemical savings. Because the bleaching plant is the biggest producer of wastewater in a pulp mill, bleaching chemical optimization reduces the environmental wastewater load.

The purpose of D₁₀₀ control is to ration chlorine dioxide (ClO₂) in the pulp flow. The ClO₂ is added just before the reactor tower. Lignin has the biggest influence on the ClO₂ dosage in the pulp after cooking (or oxygen delignification). Other variables that influence the dosage are as follows:

- Pulp consistency
- Temperature
- Inlet pulp pH
- Alkali residual after washing
- COD (chemical oxygen demand)
- Retention time in the tower.

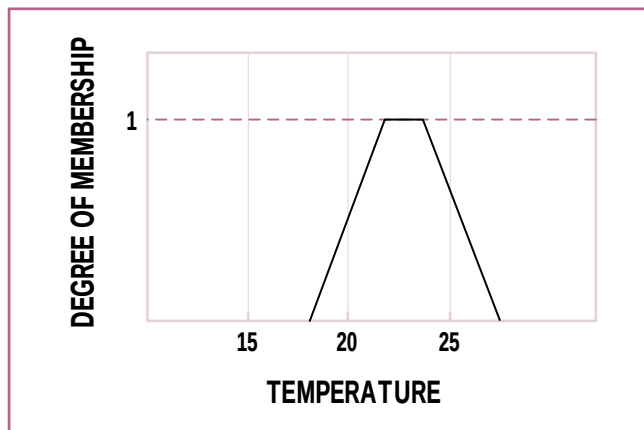
We have known the principles of fuzzy logic and fuzzy set theory for a long time. The theory of fuzzy sets was introduced by Zadeh in 1965 (1) and gave a general theoretic background to different applications. Today, fuzzy logic control is part of artificial intelligence. Most

control applications were developed during the 1980s, and recently even more applications and commercial products have been reported. Various computer programs and program packages for the development and installation of fuzzy logic control exist (2) and much research work is carried out in universities and research institutes. Commercial industrial controllers for fuzzy logic control are already on the market. However, the number of actual industrial applications, including the pulp and paper industry, is still low (3, 4).

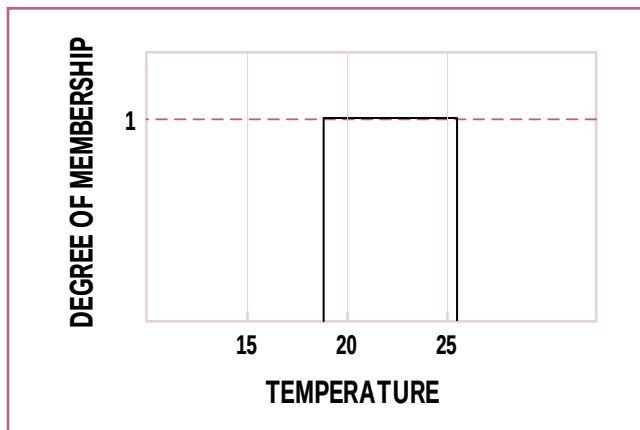
Fuzzy logic control is a mechanism that adapts control rules devised by operators and uses them in automatic control systems. This kind of control allows for uncertainties and inaccuracies in process control. Because most industrial processes are in fact nonlinear, especially when the whole operational range is considered, fuzzy logic control methods make it possible to improve the performance of conventional control. Improved product quality, increased uptime of the process, and decreased environmental load caused by disturbances and shutdown of continuous processes are benefits.

WHAT IS FUZZINESS?

"Fuzziness" is a concept that tries to describe inaccuracies and uncertainties that are common in everyday discussions but are impossible to deal with using mathematical tools. It represents a set of methods that use linguistic variables and descriptors in process control. For example, when we speak about temperature, we describe it using words such as "cold," "cool," "normal," "warm," and "hot." These linguistic expressions do not describe exact values but a range of vague values. We can



1. Fuzzy description for a "variable normal room temperature"



2. Crisp description for a variable "normal room temperature"

describe normal room temperature with a fuzzy variable, however (Fig. 1).

Figure 1 depicts that no exact one-valued limits are set by the fuzzy variable "normal room temperature," but it can have inaccuracy or uncertainty connected with it. We see this difference when we compare the fuzzy description in Fig. 1 with the crisp mathematical description in Fig. 2. These figures can be interpreted so that the crisp valued mathematics is only a subset of more versatile fuzzy mathematics. Common mathematics cannot deal with expressions such as "almost normal room temperature" or "little over normal room temperature," but fuzzy logic can.

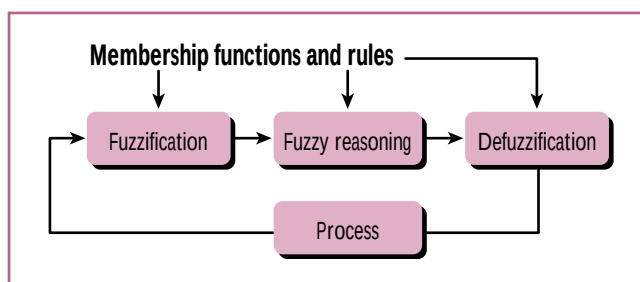
As a tool, fuzzy logic control can transfer the operator's knowledge in a linguistic form into a controller; that is, we adapt operator experience as a part of control algorithms in the same form as in human reasoning. Instead of exact numerical values, fuzzy logic controllers operate with values such as low, high, medium, sufficient, etc. This form of presentation also helps in collecting knowledge from people who are used to speaking in qualitative terms rather than in numerical values. It also has several advantages in building operator interface for control systems.

Fuzzy logic control can take different forms in a common feedback control loop. It can

- Form the only element in the control loop
- Complete a good working PID-controller that misses some important property
- Be installed on the supervisory-control level
- Give parameters or set points to lower-level controllers.

We can also connect several fuzzy controllers to form an extensive control system.

Fuzzy controllers have three main parts: fuzzification, fuzzy reasoning, and defuzzification (Fig. 3). In operation, a fuzzy controller uses membership functions (resembling one shown in Fig. 1 for "normal room tem-



3. Structure of fuzzy logic controller

perature") and rule sets. Fuzzification means the methods and principles used when converting exact measurement values to linguistic variables. In principle, fuzzification happens by dividing the measurement range into as many subareas (labels) as seems reasonable. Fuzzy reasoning is based on rules that use the fuzzified measurement values. Rule 1 is an example: If temperature is "cold" and "decreasing," then the heater valve is "increased a lot."

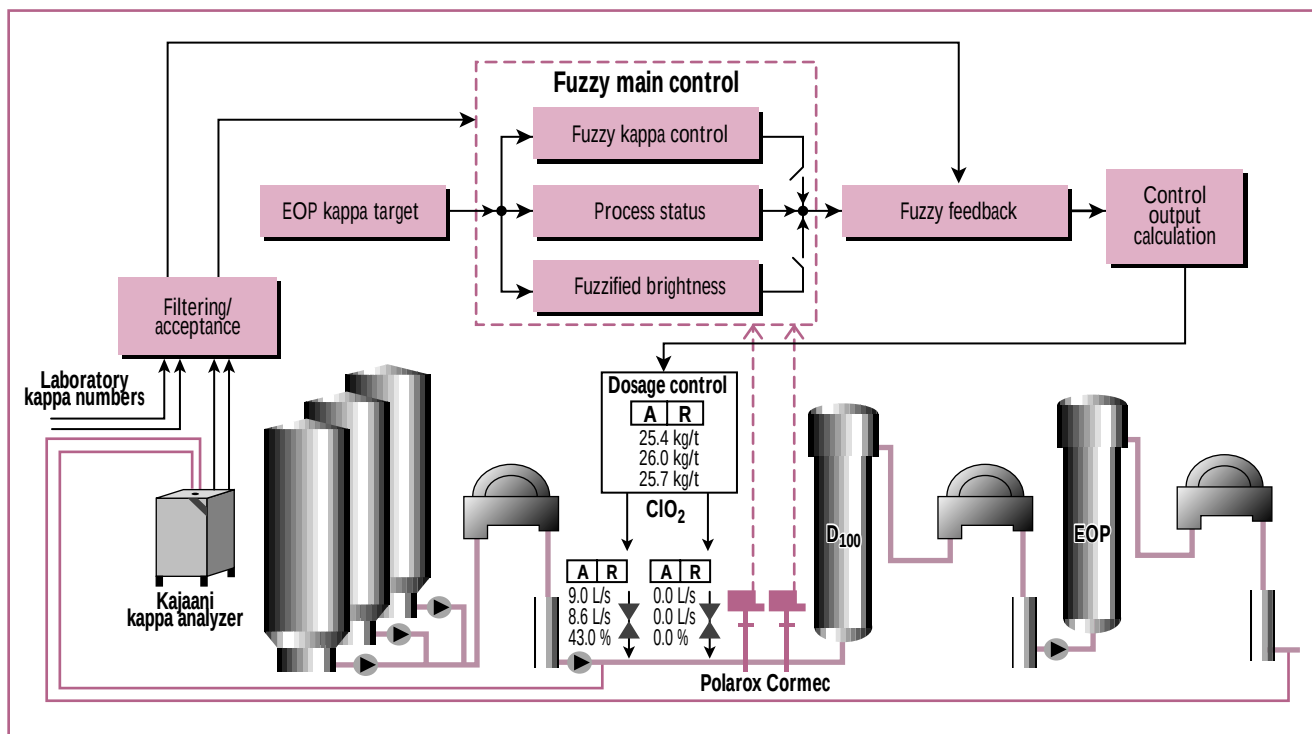
We need defuzzification for converting the fuzzy output values to the crisp values used in the real world, e.g., into valve position.

FUZZY LOGIC IN PULP BLEACHING

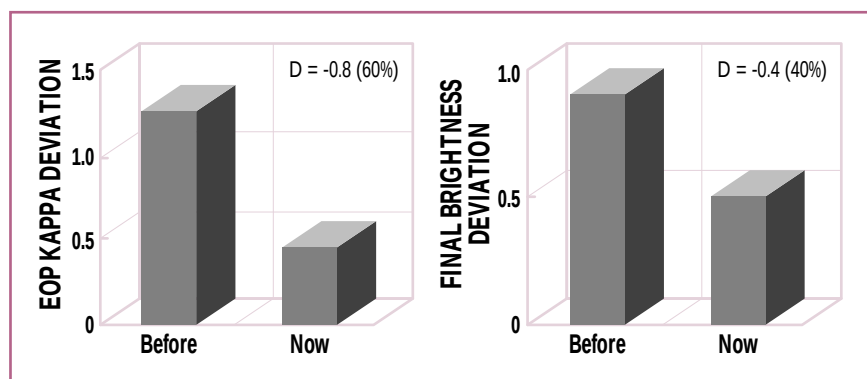
The chemical wood processing industry uses natural material—wood—that causes constant changes because of its complicated structure and properties. Many wood-fiber treatment processes are typically nonlinear—for example, the behavior of kappa number in relation to cooking conditions and brightness development vs. chemical dosages. In the bleaching process, it is also typical that process variables are highly interdependent and therefore complicate process modeling.

Several properties make fuzzy logic very suitable in developing D_{100} -stage control:

- Reaction is nonlinear, i.e., optimal control tuning is dependent on the operating point.



4. Structure of fuzzy logic control in D_{100} stage



5. EOP-kappa and final brightness deviations

- Raw material is heterogeneous, which complicates process modeling.
- Process variables depend on each other, further complicating process modeling.
- Several different process variables affect the optimal ClO_2 dosage. With fuzzy logic, it is possible to show operators the effect of different process variables on the control.
- Fuzzy logic allows for continuous measurements such as kappa analyzer or, if needed, laboratory analysis.
- Operators' and engineers' knowledge of the process behavior is easy to add to the control algorithm.

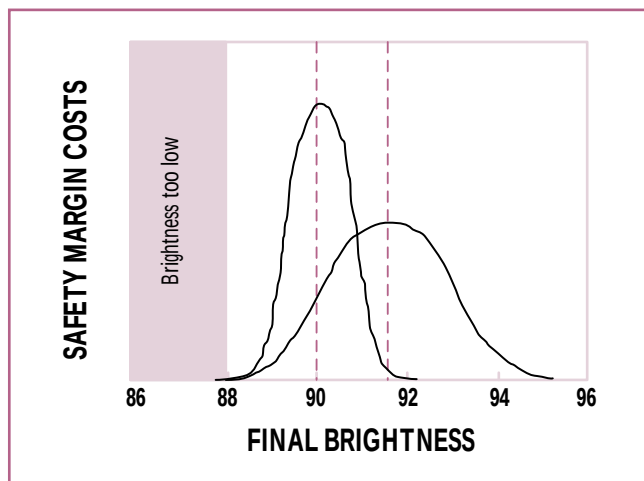
CONTROL SOLUTION

D_{100} -stage control observes the following variables:

- Inlet kappa, on-line measurement
- Inlet pulp brightness after the chemical dosage
- Chemical residual after the dosage

- Temperature
- Production rate
- Inlet pulp pH
- EOP kappa, on-line measurement.

In bleaching, we use reasoning rules such as the following: "If kappa is *increasing* and brightness is *decreasing* and pH is *increasing*, then *more* chlorine dioxide is needed." Due to the hierarchical and modular structure, the application is flexible and easy to maintain. The fuzzy controller has been applied in the Damatic™ XD control system. The control output provides the setpoint to the dosage controller, which keeps the ratio even between chemical flow and production. The feed-forward control uses Kajaani™ kappa analyzer and Kajaani Cormec and Polarox measurements of pulp brightness and chemical residuals before the D_{100} stage. Also, the feed-forward control uses the inlet pulp pH measurement and, if present, COD and conductivity measurements. The feedback controller compares the on-line EOP kappa values to setpoint and then calculates the



6. Advanced controls can reduce the margin of safety.

necessary correction for the feedforward control. Together the brightness and residual sensors with the kappa analyzer provide both feedforward and feedback measurements for improved control. Figure 4 shows the control structure and the connections between controllers.

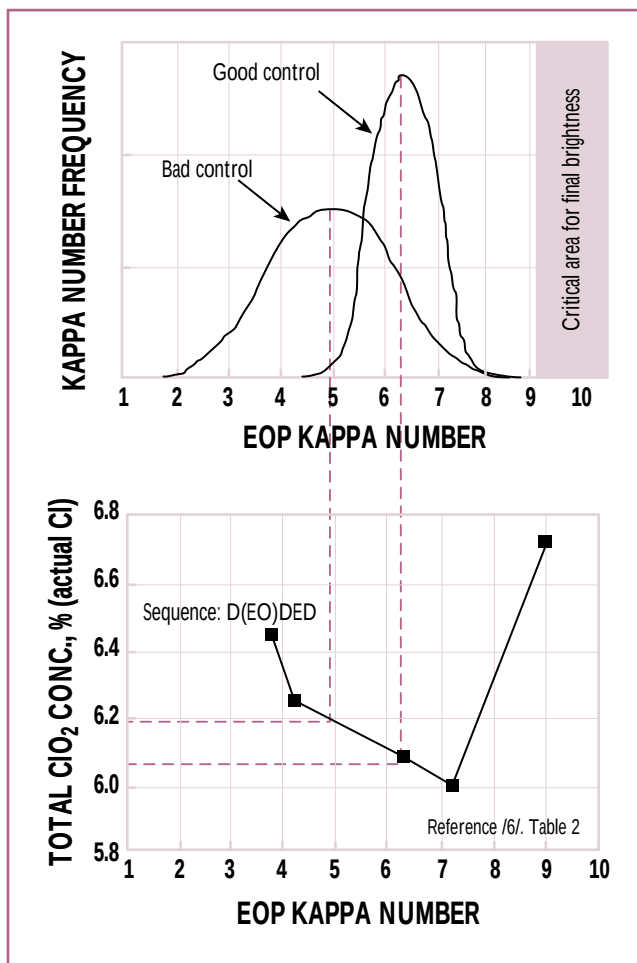
RESULTS AND EXPERIENCES

We installed the pilot control in the Kymmene Oy Wisaforest pulp mill at Pietarsaari in Finland and had excellent results. The bleach line is conventional five-stage (D_{100} -EOP-D-EP-D) bleaching. The installation procedure was smooth. We calculated the controller-tuning parameters in advance according to the process knowledge and the analyzed process data. By using these preset parameters, control was so accurate that no additional tuning was necessary.

The EOP-kappa deviation of the mill decreased about 60% during a three-week test period. As a result, deviations in final brightness also decreased by close to 40%. Due to a more consistent bleaching process, the deviation in other properties such as viscosity decreased as well. The change in EOP kappa and final brightness deviation is shown in Fig. 5.

In the bleaching process, adding more chemicals beyond a certain point yields a smaller gain in brightness. Operators tend to use more chemicals than necessary to make sure that they achieve the final brightness target. As Fig. 6 illustrates, this margin of safety can be reduced with the use of advanced controls (5). Also, the kappa factor that minimizes total ClO_2 consumption in five-stage ECF sequences is surprisingly low—approximately 0.12 (see Fig. 7) (6, 7). In addition, good control of the D_{100} stage reduces yield losses and provides chemical savings for the following bleaching process. In bleaching, even a small decrease in yield loss has significant economical meaning.

The operators in the pilot plant were actively involved when we made the final tuning. Their state-



7. Optimal EOP kappa number is surprisingly high. Advanced control can keep EOP in optimal area.

ments of the control solution have been positive. The fuzzy logic rule base was found to work well. After this final tuning period, the operators explained that the control “works as if I were doing it.”

After the tuning and the test period, the fuzzy control was left at the mill for trial use. EOP-kappa deviation stayed at the same level when compared with the test period. Raising the EOP kappa target step by step has benefited the kappa deviation improvement since the startup. Calculated chemical savings were about 3–4% on the whole line, and the operators became used to the new controller. After three months, the mill decided to buy the control for production use.

CONCLUSION

The success in D_{100} -stage control has a significant meaning for optimizing the total chemical costs of the bleaching plant. The chemical savings will provide a good ROI. The reduction in chemical use has a positive effect on the environment and simultaneously reduces the yield loss. Advanced fuzzy logic-based control for the bleach plant is an excellent investment with a very short pay-back time.

Due to the positive experiences (3, 4) with the fuzzy controls, Valmet Automation has decided to apply this technology to other pulp mill processes. Other modern control theory methods such as neural network technology are being investigated for their potential to improve the control of pulp production. TJ

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LITERATURE CITED

1. Zadeh, L. A., *Information and Control* 8: 338(1965).
2. Juuso, E. K., Myllyneva, J., and Leiviskä, K., *1994 European Simulation Multiconference Proceedings*, Society for Computer Simulation International, San Diego, Calif., p. 475.
3. Haataja, K., Ruotsalainen, J., and Ahava, O., *1995 Automation Days Conference Proceedings*, Finnish Society of Automation, Helsinki, pp. 342-346.
4. Mikkonen, J., Koskinen, J., and Hanhinen J., *Paperi ja Puu* (Paper and Timber) 76(5): 314(1994).
5. Fadum, O., *Fadum Report* 14(9): 1(1994).
6. Malinen, R., Rantanen, T., and Rasimus, R., *TAPPI 1993 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 925.
7. McDonough, T. J., *Tappi J.* 78(3): 55(1995).