ENHANCING KAPPA NUMBER CONTROL IN DOWNFLOW LO-SOLIDS^{TM} DIGESTER USING DIAGNOSIS AND MODELLING

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Abstract: In this study, Kappa number prediction and diagnosis in continuous Downflow Lo-Solids^{TM} cooking application is investigated. Gustafson's Kappa number model is applied for the prediction of the blowline Kappa number. New cooking temperature set point is solved iteratively based on the difference between the predicted and target blow-line kappa numbers. The main active variables for the Kappa number are monitored using self-organizing map (SOM). The diagnosis and Kappa control are combined into a fault tolerant system. The data is collected from industrial continuous Downflow Lo-Solids^{TM} cooking digester. Good results were achieved using the proposed approach.

1 INTRODUCTION

The question how the overall system of the sub processes and chains of sub processes can be improved, by means of fault diagnosis (see e.g. (Isermann, 1997), (Venkatasubramanian et al., 2003a) and (Venkatasubramanian et al., 2003b)), has not fully answered. In particular, this holds for demanding process conditions such as found in chemical and mechanical pulping. Modern processes generate a lot of information, which can be used for improving the operation of the process and quality of the products. This can be accomplished by combining expert knowledge, modelling, control and fault diagnosis.

The pulp digester is very important unit operation in the chemical pulping plant. The control actions in the digester have effects to the entire fiber line operations. Also the quality of the pulp in the digester should be achieved with minimal cooking costs. (Leiviskä, 2000) The quality of the chemical pulping is characterized e.g. by the pulp's strength, viscosity, yield and Kappa number. Usually only Kappa number is measured on-line. The on-line measurement is located in the blow line of the digester. Thus, the main control actions are observed only after the delay time of the cooking and washing zones. The delay time can be several hours. By the prediction of the Kappa number prior to the cooking zone more information is provided to be applied in accurate control actions. The prediction indicates changes in the blow line Kappa number. The main control of the pulp quality should be applied in the pulp digester. The control of the pulp quality is more challenging in the following subprocesses of the plant, if the pulp quality (Kappa number) is out of the good quality area after the digester.

The fault diagnosis is needed to ensure accurate quality control of the chemical processes. Diagnosis of the chemical processes are studied in many papers, see e.g. ((Dash et al., 2003) and (Qian et al., 2003)). In the field of chemical pulping, there are not too many publications concerning fault diagnosis. Puranen (Puranen, 1999) has formed a disturbance index for process operators to be able to observe faulty process situations. In that study measurements, means and deviations are combined by fuzzy logic. Diagnosis of the digester has been also studied in papers (Ahvenlampi et al., 2005) and (Tervaskanto et al., 2005).

In large industrial plants, every sub process has its own task and the entire plant is working properly if all the sub processes are functioning effectively. A faulty operation in one sub process usually changes the performance of the entire plant. Therefore, faults

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have to be found as quickly as possible and decisions that stop the propagation of their effects have to be made (Blanke et al., 2003). Active Fault Tolerant Control (AFTC) detects and isolates possible faults in the system and also reconfigures the control law (Mahmoud et al., 2003). In paper (Simani and Patton, 2002), a robust model-based technique for the diagnosis of faults in a chemical process has been developed. The system consists of a fuzzy combination of Takagi-Sugeno models. Fault Detection and Identification (FDI) is then applied by using residual analysis and geometrical tests.

In this study a continuous kraft cooking application is investigated. Most of the kraft pulp is produced in the continuous digesters (Gullichsen, 2000). In a typical chemical pulping process, the pre-treated and penetrated wood chips are fed into the impregnation vessel and pulp digester where lignin is removed from the chips with the aid of chemical reactions. The main active variables for the Kappa number are temperature, alkali concentration, cooking (residence) time and the wood species. The main lignin removal takes place in the cooking zone in the digester, where the temperature is significantly higher than in the impregnation vessel.

Applied Kappa number model (Gustafson's Kappa number model (Gustafson et al., 1983)) is also used in the real-time Kappa number modeling. The results for the conventional cooking process are presented in paper (Rantanen et al., 2003) and in the Downflow Lo-Solids^{TM} cooking process in paper (Rantanen et al., 2005).

In earlier study by the authors (Ahvenlampi et al., 2006), the proposed system was applied for the conventinal kraft cooking process. In this paper, the same approach is tested with Downflow Lo-Solids^{TM} kraft cooking process.

The aim of this approach has been to improve the Kappa number control by combining diagnosis (Ahvenlampi and Kortela, 2005) and new control strategy for Kappa number control (Rantanen, 2006). The used monitoring method is self-organizing map (SOM) (Kohonen, 1997). The evaluation of the problems in the process is performed by quantization error. If the quantization error is notable, the Kappa number prediction has been stopped.

The blow line Kappa number is predicted before cooking zone. Thus, the cooking temperature can be controlled. In the Kappa number control strategy, the cooking temperature's set point is determined by using only the Kappa number model.

The structure of the paper is an following. The methods used are presented in chapter 2. The proposed fault tolerant control system is presented in the chapter 3. Case study is considered in chapter 4 and discussion and conclusions are shown in chapters 5 and 6.

2 METHODS USED

In this chapter, methods used are presented. Empirical and experimental methods were applied. Gustafson's Kappa number model is an empirical model for delignification. The monitoring method, SOM, (Kohonen, 1997) is also presented.

2.1 Gustafson's Kappa Number Model

Gustafson *et al.* (Gustafson et al., 1983) have derived a mathematical model consisting of a series of differential equations describing the combined diffusion and kinetics within a wood chip during the kraft pulping process.

The lignin removal in the impregnation vessel can be calculated using Gustafson's Kappa number model for the initial phase. The rate equation for the initial phase delignification is:

$$\frac{dL}{dt} = k_{il} e^{(17.5 - 8760/T)} L \tag{1}$$

where L is the lignin content at time t,
k_{il} is a species specific constant and
T is temperature in Kelvin.

The rate equation for the bulk phase (cooking zone) delignification is:

$$\begin{aligned} \frac{\partial L}{\partial t} &= k_{0bl} e^{(A_l - B_l/T)} \left[OH^-\right] L + \\ & \quad k_{1bl} e^{(A_2 - B_2/T)} \left[OH^-\right]^{0.5} \left[HS^-\right]^{0.4} L, \end{aligned} \tag{2}$$

where $[OH^-]$ is the hydroxyl ion concentration,
$[HS^-]$ is the hydrosulphide ion concentration and
k_{0bl}, k_{1bl}, A_1, A_2, B_1 and B_2 are species specific constants.

The relative reaction rate is higher in the bulk phase than in the other phases.

Residual delignification happens in the washing zone and it is formulated as:

$$\frac{\partial L}{\partial t} = k_{rl} e^{(19.64 - 10804/T)} \left[OH^-\right]^{0.7} L, \tag{3}$$

where k_{rl} is a species specific constant for residual delignification.

The relative rate decreases, and the effect of hydroxyl ion concentration decreases in the residual phase. Parameters k_x, A_x and B_x are presented in (Rantanen, 2006).

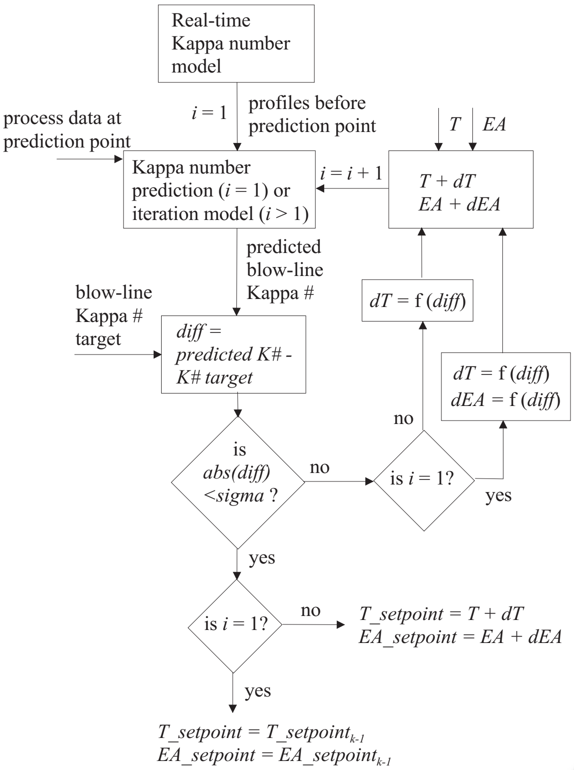

Figure 1: Structure of the new Kappa number control strategy.

2.2 Self-organizing Map

The SOM (Kohonen, 1997) is an unsupervised artificial neural network. The network is normally a two-dimensional mapping / projection of the data group. The visualization of the map is easier with a two-dimensional map. In the training of the SOM network, data points are sequentially introduced to the SOM. In each iteration, the SOM neuron which is closest to the input unit is selected by the equation (4). This unit is the Best Matching Unit (BMU) or winner.

$$\|z - c_c\| = \min_i \{\|z - c_i\|\} \tag{4}$$

where z is input vector,

c_c is the selected center, Best Matching Unit (BMU), and

c_i is the current center in the evaluation.

The weight vectors are updated using the following formula. Only the weight vectors which are inside the neighborhood radius h_{ci}, are updated.

$$c_i(t+1) = c_i(t) + h_{ci}(t)\left[z(t) - c_i(t)\right] \tag{5}$$

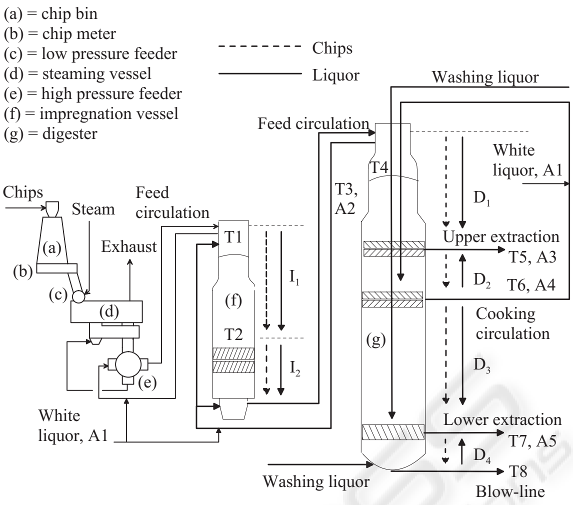

Figure 2: Impregnation vessel and continuous cooking digester.

3 KAPPA NUMBER CONTROL

In industrial plants, the Kappa number control is usually performed by the H-factor (Vroom, 1957). The H-factor expresses the cooking temperature and time as a single variable. Based on the difference between the predicted Kappa number and the Kappa number target the H-factor and temperature profile are corrected. One weakness of the H-factor is that depending on the variations in chip quality etc. different H-factors are needed, although the process conditions were otherwise the same. To overcame this problem new methods have been introduced. In this paper, Kappa number control strategy with and without a fault tolerant part is presented.

3.1 Kappa Number Control Strategy

New Kappa number control strategy is presented in study (Rantanen, 2006). In the approach, only Kappa number model is applied. That is the main difference compared to the use of Vroom's H-factor and Hatton's Kappa number model (Hatton, 1973). Thus, no separate models are needed to cover the effects of temperature, chemical concentrations and cooking time. The control of the alkali profile could also be improved by using the Kappa number model. In this paper, only temperature control is considered.

The procedure of the strategy is depicted in Figure 1. The blow line Kappa number is predicted before the cooking zone - in the middle of the Downflow Lo-Solids^{TM} digester (Figure 2). Predicted temperature and alkali profiles of the cooking zone, and online modelled Kappa number profile and process data

Table 1: Variables for the monitoring system before cooking zone (BCZ).

Variable	Unit
Alkali concentration BCZ	g/l (Na_2O, EA)
Temperature BCZ	K
Production rate BCZ	adt/d
Kappa number BCZ	

before cooking zone are used as inputs to the Kappa number prediction model. New temperature set point is solved iteratively based on the difference between the predicted and target blow line Kappa numbers. Also other process conditions, especially alkali profile, can be more precisely taken into account in the applied strategy.

3.2 Fault Tolerant Kappa Number Control Strategy

The fault tolerant control system (see structure in Figure 3) is formulated by the combination of diagnosis and control of the Kappa number in the continuous cooking plant. The self-organizing map (SOM) is applied for the monitoring purposes. The SOM is trained with normalized data. The inputs for the monitoring system are presented in Table 1. The quantization errors are used in the coloring of the trends of the measured inputs and the predicted Kappa number.

With the aid of the diagnosis part the problematic process conditions and measurement failures can be detected. If the process is not in the good operation area, the control of the Kappa number can be stopped and keep in the current state for the period of the poor operation. This ensures that the corrections are not done into wrong directions and there is not too strong corrections (overshoot).

Without monitoring problems can occur, due to the residence time between the cooking temperature control point (before cooking zone) and on-line Kappa number measurement. Inaccurate control can also bring other difficulties into the process. One of the problems is faulty packing in the digester. Faulty packing can occur, if the chips are cooked too long or too short a time. Due to the problems, also the shutdown of the process is possible.

4 CASE STUDY

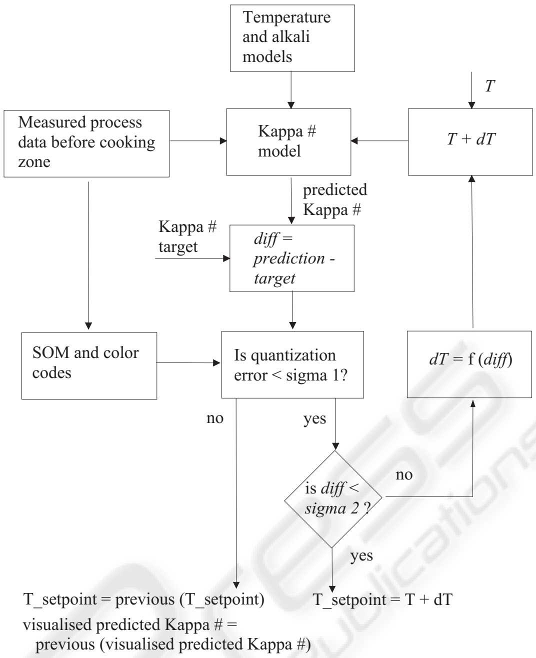

Figure 3: Structure of the fault tolerant Kappa number control system.

Case study is Downflow Lo-Solids^{TM} Kamyr process consisting of an impregnation vessel and a steam / liquor phase digester (Figure 2). The chips are impregnated in the impregnation vessel (I1-I2) and in the first zone (D1) of the digester. Between upper extraction and cooking circulation there is a counter-current washing zone (D2). In this zone, black liquor is displaced with cooking circulation liquor which temperature and alkali concentration are high. The lignin is mainly removed in the comparatively long co-current cooking zone (D3). At the bottom of the digester there is a short washing zone. Softwood chips mainly consist of pine chips with a small amount of spruce chips. Hardwood chips consist mainly of birch chips with a small addition of aspen chips.

In Downflow Lo-Solids^{TM} cooking, the Kappa number control is mainly performed by the cooking zone temperature and alkali in the middle of the digester (prior to D3).

In this study, fault tolerant control system is used for monitoring and control purposes in Downflow Lo-Solids^{TM} continuous cooking digester. The inputs to the system are monitored and the blow line Kappa number is controlled. The blow line Kappa number is predicted at the middle of the digester by using prediction model (Gustafson's Kappa number model) and the new temperature setpoint is calculated. The study is carried out in Matlab environment using measurements from the industrial continuous kraft cooking application.

The monitoring is carried out by using SOM. The modeling data (about one month data) was collected from the industrial continuous digester during its normal operation. The outliers and faulty measurements

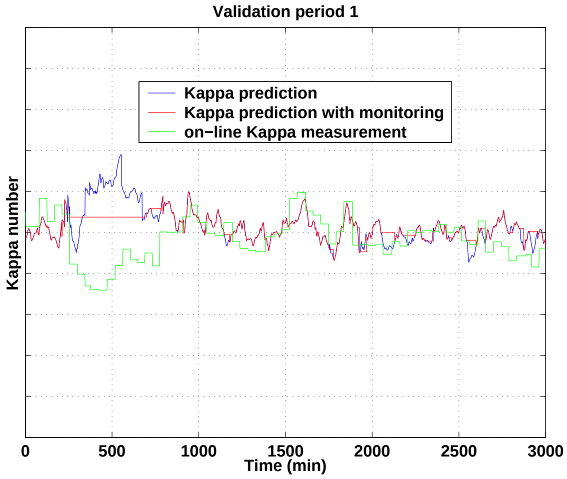

Figure 4: Validation period 1.

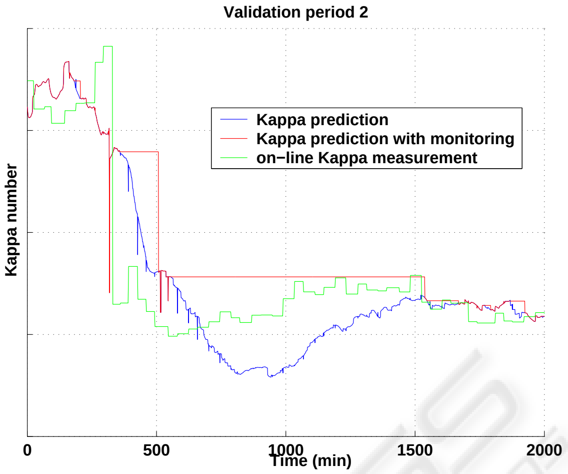

Figure 5: Validation period 2.

are filtered out from the data. The inputs are temperature, alkali, lignin content (Kappa number) and production rate before the cooking zone. The system is validated with the data from the same industrial digester, but from the different time periods.

In the Figures 4 - 6, are presented validation results of the proposed system. The monitoring system indicates, whether the prediction can be trusted or not. The stopping of the prediction is shown in Figure 4 in the time period 250-750.

Other example is shown in Figure 5, where the prediction after the grade change has not been good and it has shifted into wrong direction. The monitoring system has indicated problems in the process and the prediction has been stopped in time period 600-1500.

The same kind of example is shown in Figure 6. The prediction has been stopped for the period 600-1100.

5 DISCUSSION

The sampling interval of the on-line Kappa number measurements is about half an hour. Hence, it is useful to also get continuous information about quality properties. The accurate control can decrease significantly problems in the digester. The proposed system is a combination of diagnosis, prediction and control of Kappa number in the continuous kraft pulping digester. This kind of systems can be very helpfull for the operators.

The proposed fault tolerant control system gives new information for the control and the control actions are not taken into wrong directions as seen in Figure 4. In Figure 4 in time step 250-750, the prediction without monitoring is shifted dramatically too up and the control action would have been too strong into wrong direction. This has been avoided using monitoring and the stopping of the prediction.

In the Figures 5 and 6, are shown examples when there has been problems in the process after the grade change from softwood to hardwood. Diagnosis system has indicated problems and the Kappa number prediction has been stopped for these faulty periods. In the validaton period 2 (Figure 5), the prediction is stopped for the period 600-1500 and in the validation period 3 (Figure 6) for the period 600-1100.

The approach has been tested using the data from the industrial Downflow Lo-Solids^{TM} continuous cooking digester. Although the results are good, more research is needed to ensure the proper functioning of the proposed system in all operation points. Both prediction and diagnosis parts need some development in the future.

6 CONCLUSION

In this study, the combination of empirical and experimental methods for the diagnosis and monitoring of Kappa number control in Downflow Lo-Solids^{TM} cooking application was considered. Modeling and prediction of the Kappa number is applied using Gustafson's Kappa number model. The SOM is used to monitor the usability of the modelling and prediction results. The quality control is applied by controlling the temperature at the middle of the digester (before cooking zone) using diagnosis results and the prediction of the Gustafson's Kappa number model. Good results were achieved using the approach.

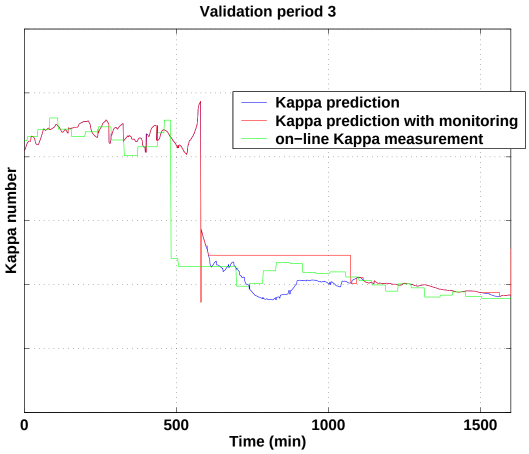

Figure 6: Validation period 3.

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