PREDICTION AND CONTROL OF BLOW-LINE KAPPA NUMBER

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Abstract: Two industrial continuous cooking processes producing both softwood and hardwood pulp were studied. Real time kappa number profiles of conventional and Downflow Lo-Solids cooking were modelled. Gustafson's kappa number model with optimised parameters was used. Blow-line kappa numbers were successfully predicted before cooking zone. New kappa number control strategy is presented. In control strategy, temperature set point is determined iteratively using prediction model of kappa number.

Keywords: pulp industry, predictive control, temperature control, product quality

1. INTRODUCTION

Most of the kraft pulp is produced in continuous digesters (Gullichsen, 2000). Typical cooking process consists of chips feeding, air removal and penetration with cooking liquor either in an impregnation vessel or in the upper part of digester. Lignin is mainly removed from the chips with the aid of chemical reactions in the digester. After the digester pulp is washed and bleached. The main control variables of cooking are temperatures and alkali concentrations. Often the only on-line measure of pulp quality is kappa number, i.e. the lignin content of the pulp, measured from the blow-line after the digester. The high production rates, large dimensions of the process equipment, inadequate measurements and variations in chip quality set demands for the control of the blow-line kappa number.

Vroom's H-factor model (Vroom, 1957) and Hatton's kappa number model (Hatton, 1973) are some of the first models describing the pulping kinetics. Although some weaknesses in these models exist, like the assumption of constant alkali-to-wood ratio, these models are still widely used in the cooking control. In Gustafson's model (Gustafson *et al.*, 1983), the changes of the temperatures, and especially the alkali concentrations in different cooking zones (initial, bulk and residual), are taken into account. That is its main advantage when compared to the widely used Hatton's model (Hatton, 1973). Many recently published papers discuss the applications of the well-known Purdue model (Wisnewski *et al.*, 1997); (Doyle and Puig, 2001); (Bhartiya *et al.*, 2003). The Purdue model including chip compaction modelling is used in the simulation and control purposes of Kamyr digesters in normal operation and in grade transitions. Important features of

Gustafson's model are the possibilities to predict the viscosity of pulp, the pulping uniformity and the amount of rejects. Gustafson's model also takes into account chip dimensions.

Gustafson's model has been applied in earlier studies by Rantanen *et al.* (Rantanen *et al.*, 2003); (Rantanen *et al.*, 2005) to model the real time kappa number profiles of two Kamyr processes. Processes were conventional Kamyr (Rantanen *et al.*, 2003) and Kamyr with the Downflow Lo-Solids cooking modification (Rantanen *et al.*, 2005). In each processes, both softwood and hardwood pulp were produced. The process conditions and flows are different in these two cooking modifications, so that more measurements and control variables are available in the Downflow Lo-Solids process, see e.g. (Marcoccia, 1996) and (Marcoccia *et al.*, 1996).

The aim of this study has been to improve the kappa number control. The blow-line kappa number is predicted in both conventional and Downflow Lo-Solids processes before cooking zone. Thus, the cooking temperature can be controlled. In the new control strategy, the cooking temperature's set point is determined by using only the kappa number model. The structure of this paper is as follows. First, Gustafson's model and the optimisations made in both softwood and hardwood cooking and grade transitions are introduced. Then case studies (conventional and Downflow Lo-Solids) are presented and modelling results are shown and discussed. In the last section the conclusions are made.

2. GUSTAFSON'S KAPPA NUMBER MODEL

Gustafson's model (Gustafson *et al.*, 1983) originally published for softwood (Scandinavian pine, *Pinus Sylvestris*) (Agarwal and Gustafson, 1997) has been applied in this study. The rate equations for both softwood and hardwood delignification with optimised constants are shown in this section.

The rate equations for delignification are shown in equations 1 - 3 (Gullichsen, 2000). The original values of the model parameters k, A and B are shown in Tables 1 and 2. The rate equation for the initial phase delignification is:

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

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

The transition from the initial phase to the bulk phase in kraft cooking takes place at a lignin content of about 22% of wood, and it is independent of temperature, sulphide concentration and alkali concentration (Olm and Tistad, 1979); (Rekunen *et al.*, 1980). The rate equation for the bulk phase delignification is:

$$\frac{\partial L}{\partial t} = k_{0bl} e^{(A_1-B_1/T)} \left[OH^-\right] L + k_{1bl} e^{(A_2-B_2/T)} \left[OH^-\right]^{0.5} \left[HS^-\right]^{0.4} L, \tag{2}$$

where $[OH^-]$ is hydroxyl ion and $[HS^-]$ hydrosulphide ion concentration and k_{0bl}, k_{1bl}, A_x and B_x are species specific constants.

The relative reaction rate and the activation energy are highest in the bulk phase. The hydroxyl ion and hydrosulphide ion concentrations have a considerable impact on the rate. The lignin content of the pulp at the transition point from the bulk phase to the residual phase may vary between 2.5% on wood (Rekunen *et al.*, 1980) and 1.1% on wood (Kleinert, 1966). The relative rate decreases, and the effect of hydroxyl ion concentration decreases in the residual phase. The rate equation for the residual phase delignification is:

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

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

Table 1. Species specific parameters in equations 1-3 (Gullichsen, 2000).

Phase of delignification	Parameter	Value
Initial phase	k_{il}	1
Bulk phase	k_{0bl}	0.15
	k_{1bl}	1.65
Residual phase	k_{rl}	2.2

In this study, the kappa number model is updated on-line, based on process data. The lignin yield is calculated in normal production and during the grade transitions. The kappa number distribution could be calculated based on the chip size distribution (Agarwal and Gustafson, 1997). However, the cooking uniformity is not calculated because of the on-line data of the chip size distributions in the mills is not available. Gustafson's model also includes equations to model the carbohydrate

Table 2. Original (Gullichsen, 2000) and optimised parameters in bulk phase.

Param.	Original value, SW	Optimised value, SW	Optimised value, HW
	Conventional process		
A_1	35.5	-	28
B_1	17200	-	16800
A_2	29.4	-	6.39
B_2	14400	-	4575
	Downflow Lo-Solids process		
A_1	35.5	29	28
B_1	17200	17000	16800
A_2	29.4	15.9	4.7
B_2	14400	8500	3800

degradation as a function of delignification, see e.g. (Ahvenlampi *et al.*, 2005). In this paper, only the delignification is considered.

2.1 Parameter optimisation

The reaction rate parameters k (Table 1) in equations 1 - 3 have been experimentally optimised, so that the lignin yields from the wood approximately obey both the values reported in the literature and the measured blow-line kappa numbers. By updating the parameters k on-line, long period changes in chip size distribution, in air removal and penetration of the chips or changes in some other process conditions can be considered. The on-line updating is based on the difference between measured and modelled kappa numbers.

The reaction rate of spruce is greater than the rate of pine (Kleinert, 1966); (Wilder and Daleski, 1965) and that difference could be taken into account by optimising the reaction rate parameters in the model (Gustafson *et al.*, 1983). In the studied cases, the softwood mainly consists of pine and the original model parameters were not changed due to a minor portion of the spruce.

One noticed that the model was too sensitive to temperature changes when using the original model parameters, especially in hardwood but also in softwood cooking. Thus, the parameters in the Arrhenius part of the bulk phase rate equation were empirically modified (Table 2). The aim was to decrease the model's temperature dependence, so that the yield remains at the same level as with the original parameters. In the original softwood parameters, 1 K change of temperature produces about a 9% change in lignin yield of hardwood (slightly dependent on process conditions). With modified hardwood parameters, 1 K change of temperature produces only about 3% change in the lignin yield in the case of conventional process. With the optimised parameters of Downflow Lo-Solids cooking, 1 K change of temperature affects to the lignin yield about 4.7% in softwood and about 2% in hardwood cooking.

The original parameters in the equations of initial and residual phase delignification are used. In Downflow Lo-Solids hardwood cooking, the model's sensitivity to the changes in process conditions is also reduced by restricting the deviation between the modelled and target kappa numbers. A certain relative difference between the modelled and target kappa numbers is allowed.

2.2 Modelling during grade transitions

Compared to the hardwood cooking, higher temperatures and lower alkali concentrations are used in the softwood cooking. Due to that, the process conditions are not ideal either for softwood or hardwood cooking during grade transitions. The usual strategy is that adequate heating for softwood cooking is ensured. The grade transition may last from 100 to 300 minutes, and during that time improper pulp quality is achieved. In a real process, the physical boundary between different species is quite clear, and during the quite long residence time the temperatures and alkali concentrations become even. Due to that, the difference between the measured and target blow-line kappa numbers is not so large. If a clear boundary between the species is assumed and parameters of normal production for both species are used, a great difference between the modelled and measured kappa number occurs. To avoid this difference, especially when visualising the results for the operators, the model parameters (Table 1) are smoothly adjusted during the transition period as a function of the temperature change in each of the digester's zones (D1-D4 in Fig. 1 and D1-D3 in Fig. 2). The adjusting of the parameters in each zone is started when new species enters the zone and is done within the zone's temperature-changing time. The parameters are restricted to between the modified values of softwood and hardwood.

3. KAPPA NUMBER CONTROL

In the kappa number control, the H-factor (Vroom, 1957) is usually used. 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. In this section, a new control strategy is presented.

3.1 New control strategy

In the new kappa number control strategy, only the kappa number model is used. That's the main difference compared to the use of Vroom's H-factor and Hatton's kappa number model (Hatton, 1973). The main advantage is that 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 determination of temperature set point is illustrated in Fig. 3. The blow-line kappa number is predicted before the cooking zone, at the top of the digester in the conventional cooking (Fig. 1), and before zone D3 in the Downflow Lo-Solids cooking (Fig. 2). Inputs for the kappa number prediction model are predicted temperature and alkali profiles of the cooking zone, and on-line kappa number profile and process data before cooking zone. New temperature set point is solved iteratively based on difference between the predicted and target blowline kappa numbers. Usually less than 10 iteration rounds are needed, when smaller than 0.1 difference between the predicted and target kappa numbers is achieved. Temperature was changed 0.2 K for the difference of one kappa number unit.

4. CASE STUDIES

4.1 Case 1 - Conventional process

Case 1 is a conventional Kamyr process consisting of an impregnation vessel and a steam/liquor phase digester (Fig. 1). The process has been substantially simplified by removing almost all of the original liquor circulations, thus only the upper and lower extraction screens in the end part of the cooking zone are used. The digester is examined in six separate zones (Fig. 1) according to the temperature and alkali measurement points. The first four zones belong to the cooking zone of the digester and the last two to the counter-current washing zone. Softwood chips consist of pine and slightly of spruce. Hardwood chips consist mainly of birch but also eucalyptus is used.

The active alkali concentrations of the white liquor, of the digester feed circulation liquor and of the two black liquor extractions from the end of the cooking zone are measured. The white liquor is added to the feed circulations of impregnation vessel and digester. The sulphide concentration of the white liquor is measured and assumed to stay constant during the cooking process. Before the latest simplifications of the process, alkali measurements were taken from the extraction screens in the upper part of the digester's cooking zone. These measurements have been utilised in the development of the alkali profile model. All alkali measurements are based on analysed samples.

Temperatures are measured from the liquor circulations, from the heating steam and from several vertical locations of the digester near the digester wall. The temperature profile of the digester's cooking zone is developed using separate models for all subzones (D1 - D4, Fig. 1). In the digester's washing zone, there are two temperature sensor circles around the digester. Both circles consist of six temperature sensors on the outside wall of the digester. One circle is right under the lower extraction screens and another circle is in the

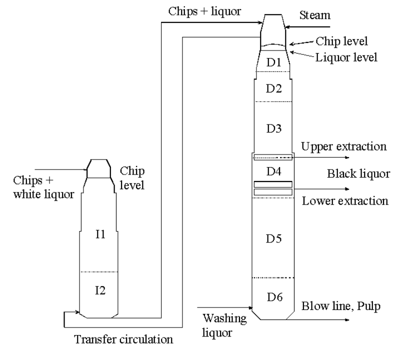

Fig. 1. Impregnation vessel and conventional continuous Kamyr digester.

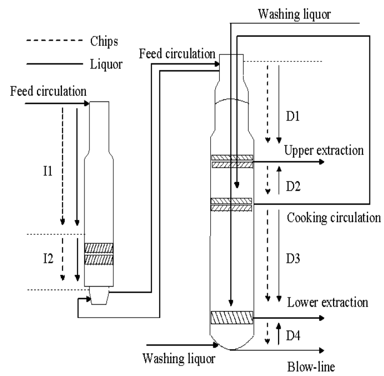

Fig. 2. Main flows in Downflow Lo-Solids cooking.

lower part of the washing zone. These sensors enable the detection of the temperature changes in both the horizontal cross-section and vertical direction of the digester.

The blow-line kappa number (Fig. 1a) is predicted at the top of the digester. The real time model is updated on-line, and the kappa number profile in the digester is re-calculated after each kappa number measurement using the updated parameters. The modelled blow-line kappa number is shown in Fig. 4b. The new control strategy is used to determine the temperature set point based on the kappa number difference (Fig. 4a). Correction required to the measured temperature is shown in Fig. 5b. In Fig. 5a the controlled kappa number is shown. Both modelled (Fig. 4b) and predicted (Fig. 4a) kappa numbers correlate well with the measurements. The control actions required to the temperature set point are realistic in both grades. Calculated modelling errors are shown in Table 3.

4.2 Case 2 - Downflow Lo-Solids process

System 2 consists of an impregnation vessel and a steam/liquor phase digester running the Downflow Lo-Solids process (Fig. 2). The digester is examined in four separate zones according to the extractions.

The chips are impregnated in the impregnation vessel and in the first zone (D1) in the digester

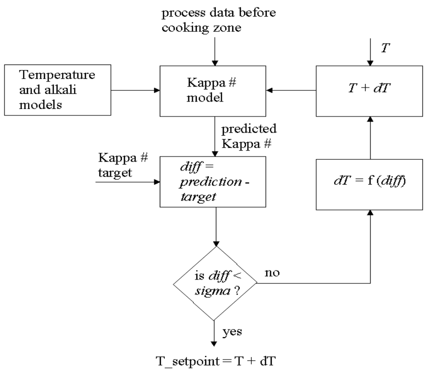

Fig. 3. Determination of temperature set point.

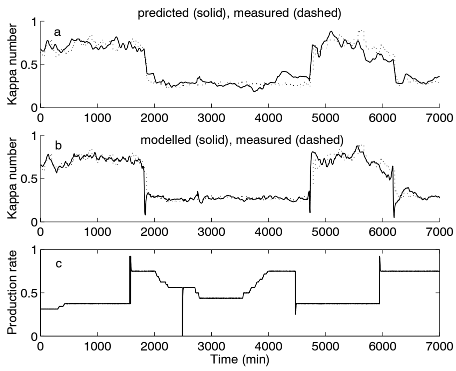

Fig. 4. Blow-line kappa numbers and production rate in conventional cooking.

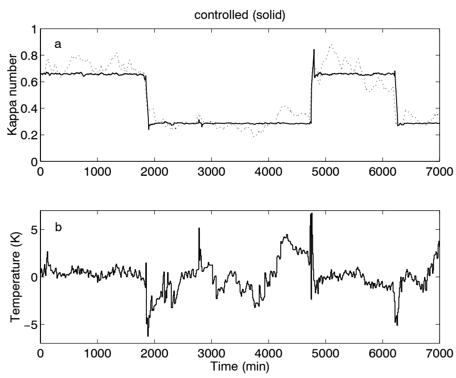

Fig. 5. Blow-line kappa numbers and correction of temperature in conventional cooking.

down to the upper extraction screens. 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, of which the 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 is a short washing zone. Softwood chips mainly consist of pine chips with a small amount of spruce chips. Hardwood chips mainly consist of birch chips with a small addition of aspen chips.

The effective alkali concentrations of the white liquor, digester feed circulation liquor, two black liquor extractions and cooking circulation are

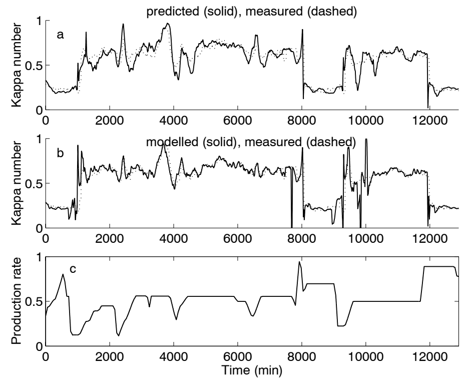

Fig. 6. Blow-line kappa numbers and production rate in Downflow Lo-Solids cooking.

measured. The white liquor is added to the impregnation vessel's feed circulation, to the digester's feed circulation and to the cooking circulation. The sulphide concentration of the white liquor is measured, and it is assumed to stay constant during the cooking. Temperatures are measured from the liquor circulations and from the heating steam at the top of the digester. A temperature profile from the top of the digester to the cooking circulation is constructed emphasizing the measured temperatures suitably. The temperature profile from the cooking circulation to the blow-line is based on the temperature of cooking circulation.

The blow-line kappa number (Fig. 6a) is predicted after zone D2. The real time model is updated on-line, and the kappa number profile in zones D2 and D3 is re-calculated after each kappa number measurement using the updated parameters. The updated parameters are also used in the prediction model. The modelled blow-line kappa number is shown in Fig. 6b. By using the new control strategy, the blow-line kappa number is calculated with the corrected cooking circulation temperature. Correction required to the measured temperature is shown in Fig. 7b. Controlled kappa number is shown in Fig. 7a. Both modelled (Fig. 6b) and predicted (Fig. 6a) kappa numbers correlate well with the measurements. The prediction model needs to be improved during the production rate changes. The control actions required to the temperature set point are realistic in both grades. Calculated modelling errors are shown in Table 4.

5. CONCLUSIONS

The blow-line kappa numbers of two cooking processes are successfully predicted. The predicted kappa numbers are utilised in the kappa number control. The new kappa number control strategy utilising the prediction model is presented and tested. The new strategy is simple, easy to implement and only few iteration rounds

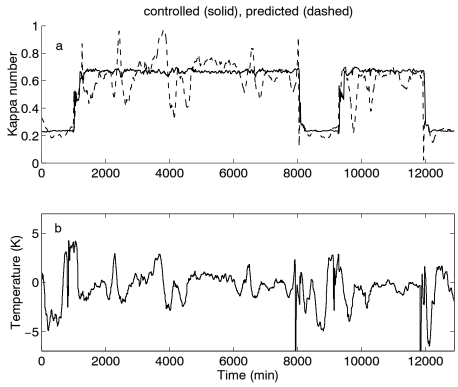

Fig. 7. Blow-line kappa numbers and correction of temperature in Downflow Lo-Solids cooking.

Table 3. Mean squared and mean errors in case study 1.

	MSE		ME	
	SW	HW	SW	HW
Pred. vs. meas. K#	0.0030	0.0007	0.041	0.020
Mod. vs. meas. K#	0.0057	0.0031	0.062	0.042
Contr. vs. target K#	0.0038	0.0014	0.017	0.007

Table 4. Mean squared and mean errors in case study 2.

	MSE		ME	
	SW	HW	SW	HW
Pred. vs. meas. K#	0.0058	0.0008	0.057	0.024
Mod. vs. meas. K#	0.0001	0.0005	0.054	0.018
Contr. vs. target K#	0.0001	0.0001	0.008	0.004

are needed. The new control strategy has been implemented into the industrial automation system.

6. ACKNOWLEDGEMENTS

This research study was funded by Stora Enso Oyj, Metsä-Botnia Oy, Andritz Oy, Metso Automation Oy and the National Technology Agency (Tekes). The authors would like to thank the partners for the special knowledge and process data provided.

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