Modeling of Kappa number in Downflow Lo-Solids cooking using Gustafson's model

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Modelling of kappa number in Downflow Lo-Solids cooking using Gustafson's model

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Abstract: Gustafson's kappa number model has been applied to the modelling of an industrial Downflow Lo-Solids cooking process. The model parameters have been optimized to be suitable in both softwood and hardwood cooking. The real-time kappa number profile of an impregnation vessel and digester has been calculated. Based on a real- time model and process measurements before cooking zone, the blow-line kappa number has been successfully predicted. The modelling results will be utilized in control purposes.

In an earlier study by the current authors, Gustafson's model [1] has been applied to the modelling of the kappa number profile of a traditional Kamyr process [2]. In Downflow Lo-Solids cooking [3, 4] the process and flow conditions differ from the ones of the traditional Kamyr. The cooking reactions are, however, the same in both processes and more measurements and control variables are available in the Downflow Lo-Solids process.

In Gustafson's model [1], 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 [5]. Many papers recently published discuss the applications of the well-known Purdue model [6, 7, 8]. 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. Because of the features mentioned above and because the model is quite easy to implement into the plant's automation system, Gustafson's kappa number model [1] was chosen.

The chief aim has been to apply Gustafson's model to the Downflow Lo-Solids cooking and to model the real-time kappa number profile of the complete cooking process. The second goal has been to improve the predictability of the blow-line kappa number. The results will be used in the monitoring and control of the kraft cooking. The main interest has been in softwood cooking because the process conditions in softwood cooking affect the kappa number more than in hardwood cooking.

The structure of the paper is as follows. First, the Downflow Lo-Solids process and the used variables are presented. Then Gustafson's model and the optimizations carried out in both softwood and hardwood cooking and grade transitions are introduced. The results of the kappa number modelling are shown and discussed. In the last section the conclusions are presented.

PROCESS DESCRIPTION

The studied industrial scale system consists of an impregnation vessel and a steam/liquor phase digester running the Downflow Lo-Solids process, Fig. 1. 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 a digester down to the upper extraction screens. Between the upper extraction and cooking circulation there is a counter-current washing zone (D2). In this zone, chips are displaced with cooking circulation liquor, in 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 (D4). A characteristic feature of this process is the grade transitions between softwood and hardwood. Softwood chips mainly consist of pine chips with small amounts of spruce chips. Hardwood chips consist mainly of birch chips with small additions of aspen chips.

The effective alkali concentrations of the white liquor, of the digester feed circulation liquor, of the two black liquor extractions and of the cooking circulation are 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 ion concentration of the white liquor is measured and assumed to stay constant during the cooking process.

Temperatures are measured from the liquor circulations and from the heated steam at the top of the digester. The temperature profile from the top of the digester to the cooking circulation is constructed by emphasizing measured temperatures suitably. The temperature profile from the cooking circulation to the blow-line is based on the temperature of the cooking circulation.

All the data used in the study are measurements from the industrial continuous digester. All process measurements are mean values of one minute, or values of samples at sampling intervals. Calculation interval in the modelling is one minute. Data handling consisting of evaluation and filtering, model identification and simulation are carried out with the MATLAB-program.

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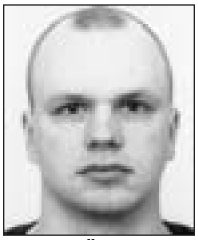

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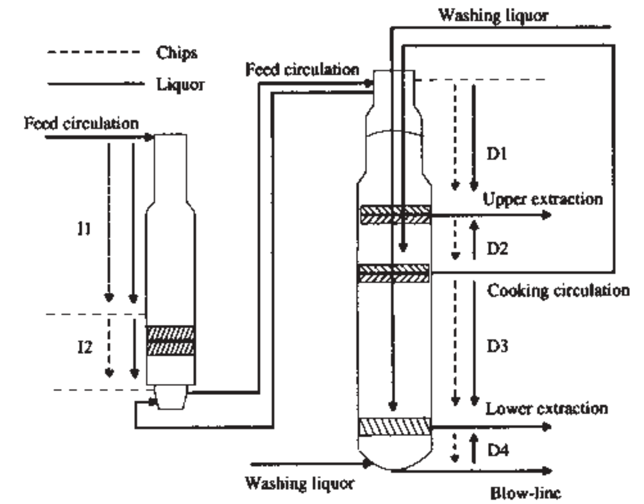

FIG. 1. Main flows and flow directions of chips and liquor in impregnation vessel and digester in Downflow Lo-Solids cooking.

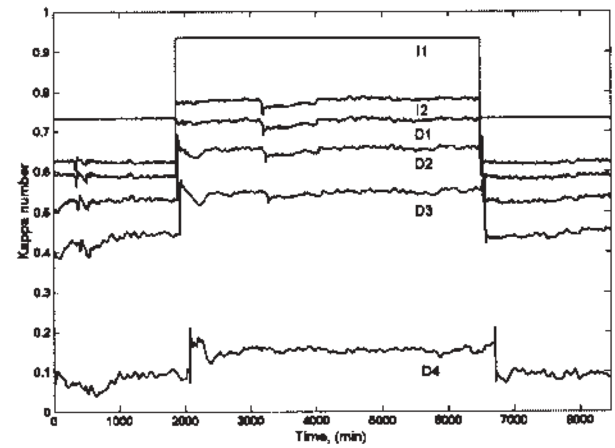

FIG. 2. Kappa numbers before zones I1 - D4.

TABLE I. Species-specific parameters in the rate equations 1-3 [10].

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

TABLE II. Original and optimized parameters of Arrhenius Equation in bulk phase.

Parameter	Original value, SW [10]	Optimized value, SW	Optimized value, HW
A_1	35.5	29	28
B_1	17,200	17,000	16,800
A_2	29.4	15.9	4.7
B_2	14,400	8,500	3,800

GUSTAFSON'S KAPPA NUMBER MODEL

Gustafson's model [1] originally published for softwood (Scandinavian pine, *Pinus sylvestris* [9]) has been used in this study. The rate equations for both softwood and hardwood delignification with optimized constants are presented in this section. The model is updated on-line, based on process data. The lignin yield is calculated in normal production and during grade transitions.

The kappa number distribution could be calculated based on the chip size distribution [9]. The cooking uniformity is not calculated because the on-line data of the chip size distribution in the mill is not available. Gustafson's model also includes equations to model the carbohydrate degradation as a function of delignification. In this paper only the delignification is considered.

The rate equations for the delignification are shown in equations 1-3 [10]. The original values of the model parameters *k*, *A* and *B* are shown in Tables I and II. The rate equation for the initial phase delignification is:

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

where L is the lignin content, % on wood; and $k_i l$ 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 ion concentration and alkali concentration [11, 12]. The rate equation for the bulk phase delignification is:

$$\frac{dL}{dt} = k_{0bl} e^{(A_1-B_1/T)} [OH^-] L + k_{1bl} e^{(A_2-B_2/T)} [OH^-]^{0.5} [\mathrm{HS}^-]^{0.4} L \qquad (2)$$

where $[OH^-]$ is the hydroxyl ion concentration; $[HS^-]$ is the hydrosulonide 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 [12] and 1.1% on wood [13]. 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:

$$\frac{dL}{dt} = k_{rl} e^{(19.64-10804/T)} [\mathrm{OH}^-]^{0.7} L \qquad (3)$$

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

Parameter Optimization: The reaction rate of spruce is greater than the rate of pine [13, 14], and that difference could be taken into account by optimizing the reaction rate parameters in the model [1]. The softwood in the study mainly consists of pine and the model parameters were not changed because of the minor portion of the spruce.

The reaction rate parameters *k*, Table I, in equations 1-3 have been experimentally optimized as a function of production rate, 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 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.

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. Because of that reason the parameters in the Arrhenius part of the bulk phase rate equation were empirically optimized, Table II. The aim was to decrease the model's sensitivity to temperature, so that yield remains at the same level as with the original parameters. In the original parameters, 1°K change of temperature produces about a 9% change in lignin yield

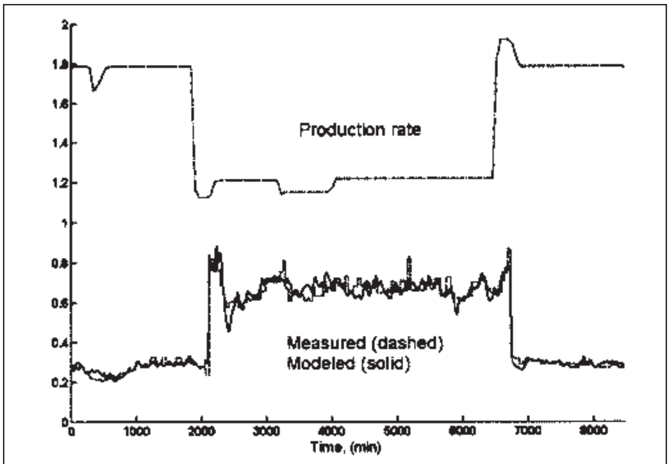

FIG. 3. Measured and modelled blow-line kappa number and production rate.

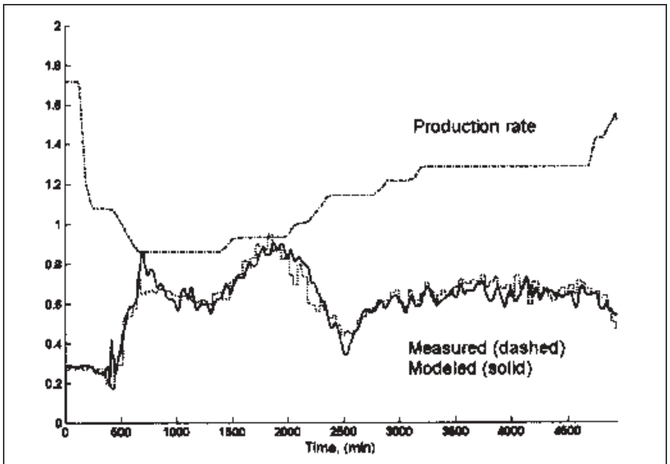

FIG. 4. Measured and modelled blow-line kappa number and production rate.

of hardwood (slightly dependent on process conditions). With optimized parameters, 1°K change of temperature produces about 3% change in the lignin yield. The original parameters in the equations of the initial and residual phase delignification are used. In 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.

Kappa Number Modelling During Grade Transitions: Compared to the hardwood cooking, higher temperatures and lower alkali concentrations are used in the softwood cooking. This means that during grade transitions the process conditions are not ideal either for softwood or hardwood cooking. 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. Because of 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 target Kappa number occurs. To avoid this difference, especially when visualizing the results for the operators, the model parameters (Table I) are smoothly adjusted during the transition period as a function of the temperature change in each of the digester's vertical zones (D1-D4). The adjusting of the parameters in each zone is started when new species enters the zone, and is completed within the zone's temperature-changing time. The parameters are restricted to between the optimized values of softwood and hardwood.

RESULTS

The kappa number profile in the impregnation vessel (zones I1 and I2) and in the upper part of the digester (D1 and D2) is modelled based on real-time data. In the cooking zone D3, the calculation is based on process measurements before that zone. Thus, the blow-line kappa number can be predicted before the chips enter the cooking zone by using the real-time model. The washing zone is short and the calculation is simplified, so that it is assumed that the delignification ends at the lower extraction. Another reason for the simplification is that the temperature and the amount of washing liquor are not known beforehand. Equation 1 is used for modelling in zones I1 - I2, and equation 2 for modelling in zones D1 - D3.

The kappa number profile, Fig. 2, and blow-line kappa numbers, Figs. 3 and 4, are scaled. The measured values of the temperatures and alkali concentrations are not shown because of confidential reasons. The temperature and alkali measurements are used so that the constructed profiles in each zone represent the temperatures and alkali concentrations of chips. In the construction of profiles, e.g., the concentration difference between chips and liquor and the heat generated in the reactions are taken into account. The resulting kappa number profile in the impregnation vessel and digester has not been verified because a measured kappa number profile was not available. The results of the kappa number modelling are verified based on comparison between the measured and modelled blow-line kappa numbers.

The kappa numbers before each zone are shown in Fig. 2. The production rate and the predicted and measured blow-line kappa numbers of the same period are shown in Fig. 3. The production period is from summer, and includes two grade transitions. The modelled blow-line kappa number correlates well with the measured kappa number during production of both grades, and also over the grade transitions. The mean square error of scaled kappa number is 0.0018 in softwood cooking and 0.00037 in hardwood cooking. The grade transitions are not considered when calculating the error. The variance of both modeled and measured kappa number is higher in the production of softwood.

Modelled and measured blow-line kappa numbers during a production period from winter are shown in Fig. 4. That period includes grade transition and some process disturbances, resulting in kappa number fluctuations. Model parameters in Fig. 3 and Fig. 4 differ from each other because of the updating; otherwise the

Résumé: Le modèle d'indice Kappa de Gustafson a servi à la modélisation d'un procédé industriel de cuisson à faible teneur en solides dans un lessiveur en continu à courant descendant. Les paramètres du modèle ont été optimisés pour s'adapter à la cuisson tant des résineux que des feuillus. Nous avons calculé le profil de l'indice Kappa en temps réel d'un imprégnateur et d'un lessiveur. Sur la base d'un modèle en temps réel et de mesures du processus avant la zone de cuisson, nous avons pu prévoir avec succès l'indice Kappa à la conduite de décharge. Les résultats de la modélisation seront utilisés à des fins de contrôle du procédé.

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model is same in both cases. In Fig. 4 the mean square error of scaled kappa number is 0.0025 in softwood cooking.

CONCLUSIONS

The results show that Gustafson's model can be applied to the modelling of Downflow Lo-Solids cooking. The modeled kappa number correlates well with the measured kappa number giving on-line information of the process. By visual presentation of the real-time kappa number profile the operators' work can be supported. The cooking degree profile can be utilized in the considerations of the compaction of the chip column, and the kappa number prediction can be utilized in kappa number control. Future research will concentrate on the applications of the modelling results. The possibilities to utilize the real-time kappa number profile in the control of temperatures and alkali concentrations of different liquor circulations and zones in the impregnation vessel and digester will be considered.

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