VISUALIZING YIELD PROFILES IN CONTINUOUS COOKING PROCESSES

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Abstract: In industrial continuous cooking systems, yields are seldom measured on-line. In this study, profiles for lignin, carbohydrates and total yield are constructed using physical model. The yield profiles are utilized for two kinds of digesters: conventional and Downflow Lo-Solids cooking processes. The total yield is also predicted using fuzzy clustering model.

Keywords: Monitoring, operators, fuzzy logic, pulp industry, controllability

1. INTRODUCTION

Kappa number is used to measure the cooking uniformity of the pulp. There are also other quality variables, e.g. strength, viscosity and yield, but they are difficult to measure on-line. Most often the only on-line Kappa number measurement is located in the blow-line of the digester. The lack of the measurements due to the harsh process conditions set demands for the modelling of cooking. Gustafson *et al.,* (Gustafson *et al.*, 1983) have derived rate equations for the lignin and carbohydrates reactions. Modelling and prediction of the lignin yield (Kappa number) is performed in many studies (see e.g.: (Gustafson *et al.*, 1983),(Rantanen *et al.*, 2003) and (Ahvenlampi *et al.*, 2004)). Carbohydrate yields are studied in some papers (Gustafson *et al.*, 1983) and (Wisnewski *et al.*, 1997). The total yield of the pulp has major effect in the costs of the pulp processing. In this study, the total yield is composed from subyields of lignin and carbohydrates.

Most of the kraft pulp is produced in continuous digesters (Gullichsen, 2000). Typical cooking process consists of chip feeding, air removal and penetration with cooking liquor either in an impregnation vessel or in the upper part of digester. The aim of pulping is to remove lignin from the chips with the aid of chemical reactions so that quality and yield remain as high as possible. The main dissolution of the carbohydrates takes place in the impregnation vessel. Lignin delignification reactions occur mainly in the digester. After digester the pulp is washed and bleached. The main control variables of cooking are temperatures and alkali concentrations. The high production rates, large dimensions of the process equipments, inadequate measurements and variations in chip quality set demands for the control of blow-line Kappa number.

In this study, two continuous cooking processes (conventional and Downflow Lo-Solids processes) are investigated. The lignin yield profiles (Kappa number profile) for both applications are presented in the earlier studies (Rantanen *et al.*, 2003) and (Rantanen *et al.*, 2005). In this study, the carbohydrate and total yield profiles are also presented.

The total yield is predicted in conventional cooking process after the impregnation vessel using fuzzy model. Fuzzy modelling have been carried out mostly by Mamdani- (Mamdani, 1977) and Sugeno models (Takagi and Sugeno, 1985). Sugeno models have a fuzzy premise part and a piecewise linear consequent part while in Mamdani models both parts are fuzzy. In the cases of multiple input system, identification of these models needs a lot of calculations. However, to overcome this problem new methods have been proposed. Fuzzy clustering, see (Babuska, 1998) and (Bezdek *et al.*, 1999), is one of the methods to use in the identification of the non-linear processes. The use of fuzzy clustering in the partitioning makes the identification easier (less rules) and also better results can be achieved.

Structure of the paper is as follows. Processes are presented in the section 2. In the section 3, Gustafson's physical model for softwood cooking is presented. Fuzzy clustering methods are shortly revised in the section 4. Results are shown in the section 5 and conclusions are presented in the section 6.

2. PROCESSES

2.1 Conventional cooking process

Case one is a conventional Kamyr process consisting of an impregnation vessel and a steam/liquor phase digester (Fig. 1). The process has been 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. A characteristic of this process is the grade changes between softwood and hardwood done almost every other day. The active alkali concentrations of the white liquor, of the digester feed circulation liquor and of the two black liquor circulations from the end of the cooking zone are measured. The sulphide concentration of the white liquor is also measured and it's assumed to stay constant during the cooking. 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 alkali profile. Temperatures are measured from the various parts of the digester.

2.2 Downflow Lo-Solids cooking process

Case two is a Downflow Lo-Solids (Marcoccia *et al.*, 1996) cooking process (Fig. 2). The chips are impregnated in the impregnation vessel (I1-I2) and in the first zone (D1) in digester down to the

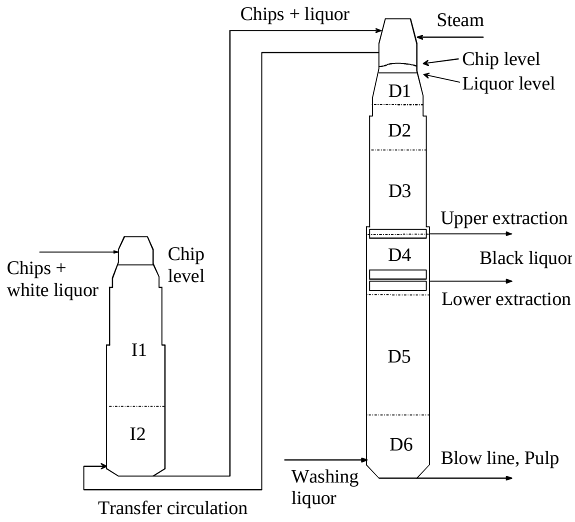

Fig. 1. Impregnation vessel and continuous Kamyr digester in conventional cooking process.

upper extraction screens. Between upper extraction and cooking circulation there is a countercurrent washing zone (D2). In this zone, black liquor is displaced with cooking circulation liquor of 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 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.

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 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 heated 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.

3. GUSTAFSON'S MODEL (YIELD PROFILES)

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 kinetics of the carbohydrates reactions are related and proportional

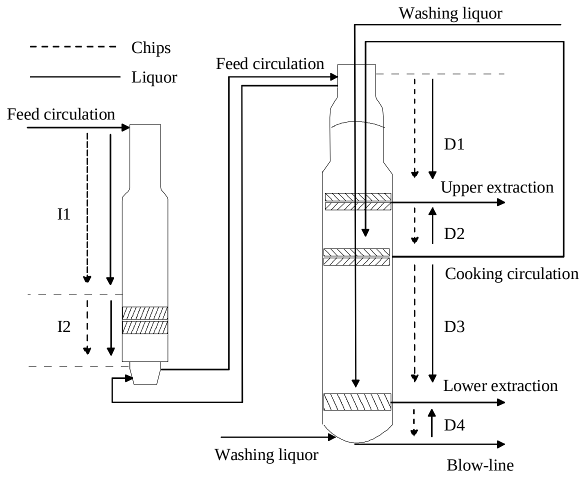

Fig. 2. Main flows and flow directions of chips and liquor in impregnation vessel and digester in Downflow Lo-Solids cooking.

to the kinetics of lignin yield as can be seen in Fig. 3 (Gullichsen, 2000).

The rate equations for delignification and dissolution of carbohydrates of the Scandinavian pine are presented in the equations 1-6 (Gullichsen, 2000). The original values of the model parameters k are presented in Table 1. The rate equation for the initial phase (I1 and I2 in Fig. 1) 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 (K) and

k_{il} is a species specific constant.

The equation of carbohydrate dissolution in the initial phase (I1 and I2 in Fig. 1) is:

$$\frac{\partial C}{\partial t} = k_{ic} \frac{\partial L}{\partial t} \left[OH^-\right]^{0.11}, \tag{2}$$

where C is the carbohydrate content at time t,

k_{ic} is a species specific constant and

$[OH^-]$ is the hydroxyl ion concentration.

The initial phase seems to be independent of the $[OH^-]$ concentration. This does not mean one can proceed through this phase without alkali but only indicates that alkali concentration does not influence the rate. The rate equation for the bulk phase (D1-D4 in Fig. 1) delignification is:

$$\frac{\partial L}{\partial t} = k_{0bl} e^{(35.5-17200/T)} \left[OH^-\right] L + k_{1bl} e^{(29.4-14400/T)} \left[OH^-\right]^{0.5} \left[HS^-\right]^{0.4} L, \tag{3}$$

where $[HS^-]$ is the hydrosulphide ion concentration and

k_{0bl} and k_{1bl} are species specific constants.

The equation of carbohydrate dissolution in the bulk phase (D1-D4 in Fig. 1) is:

$$\frac{\partial C}{\partial t} = k_{bc} \frac{\partial L}{\partial t}, \tag{4}$$

where k_{bc} is a species specific constant for bulk phase.

The relative reaction rate is higher in the bulk phase than in the other phases. The activation energy is also highest in the bulk phase. The hydroxyl ion and hydrosulphide ion concentrations have a considerable impact on the rate.

Residual delignification happens in the washing zone (D5-D6 in Fig. 1) and it is formulated as:

$$\frac{\partial L}{\partial t} = k_{rl} e^{(19.64-10804/T)} \left[OH^-\right]^{0.7} L, \tag{5}$$

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.

The equation of carbohydrate dissolution in the residual phase (D5-D6 in Fig. 1) is:

$$\frac{\partial C}{\partial t} = k_{rc} \frac{\partial L}{\partial t}, \tag{6}$$

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

Table 1. Species specific parameters in the rate equations (1-6) (Gullichsen, 2000).

Phase	Parameter	Value
Initial phase	k_{il}	1
	k_{ic}	2.53
Bulk phase	k_{0bl}	0.15
	k_{1bl}	1.65
	k_{bc}	0.47
Residual phase	k_{rl}	2.2
	k_{rc}	2.19

In this study, Gustafson's model has been utilised with the alkali and temperature profiles constructed from the process data. The alkali concentrations have been converted from Na_2O to $[OH^-]$ and $[HS^-]$ ion concentrations. The reaction rate parameters k in the equations (1) - (6) have been modified experimentally, so that the lignin intake values from the wood approximately obeys the values reported in the literature.

4. FUZZY CLUSTERING

Fuzzy clustering (Bezdek, 1981) is used in modelling, identification and pattern recognition. The

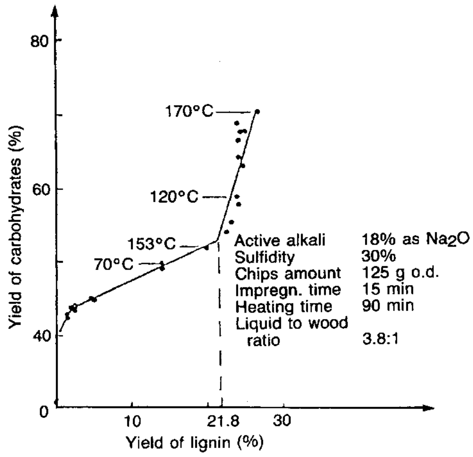

Fig. 3. Dissolution of carbohydrates and lignin during cooking. (Gullichsen, 2000)

purpose of the clustering is the classification of the data set according to the similarities and to organise the data into groups. Clusters are subsets of the data set and classification of the data can be done by fuzzy or crisp (hard) clustering. In hard clustering a data point can be only in one cluster. In many situations fuzzy clustering is more natural way to partition, because data points can be partly in many clusters. (Babuska, 1998)

4.1 Fuzzy c-means

Fuzzy c-means is a widely used algorithm for fuzzy identification (Bezdek, 1981). The FCM cost function is usually formulated as:

$$J(Z;U,C) = \sum_{i=1}^{c}\sum_{k=1}^{N} (\mu_{ik})^m D_{ik}^2, \qquad (7)$$

where $C = \{c_1, c_2, ..., c_c\}$ are the cluster centers (prototypes) to be determined, $U = [\mu_{ik}]$ is a fuzzy partition matrix (Bezdek, 1981),

$$D_{ik}^2 = (z_k - c_i)^T B (z_k - c_i) \qquad (8)$$

is a distance (norm) defined by matrix B (usually the identity matrix), and m is a weighting exponent which determines the fuzziness of the resulting clusters. Classified data in c clusters is arranged in a vector $Z = \{z_1, z_2, ..., z_N\}$.

4.2 Gustafsson-Kessel algorithm

Gustafsson-Kessel algorithm is the extension most used by the FCM for identification (Babuska, 1998). In this method, norm can be different with every cluster, and the method has the advantage of looking for variable size hyperellipsoids. The new distance to be used in (7) becomes:

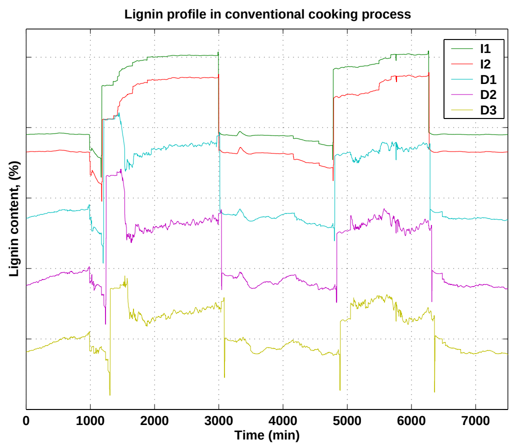

Fig. 4. Lignin profile in conventional cooking process.

$$D_{ikBi}^2 = (z_k - c_i)^T B_i (z_k - c_i) \qquad (9)$$

In this way, the existing operating regimes (local models) are detected quite correctly. Improved version of Gustafson-Kessel algorithm has been introduced by (Babuska *et al.*, 2002).

4.3 Number of the clusters

The decision of the number of the clusters is perhaps the most critical point in fuzzy clustering. Many methods have been introduced for the selection of the clusters, see e.g. (Babuska, 1998) and (Bezdek *et al.*, 1999).

Fuzzy hypervolume (Gath and Geva, 1989) is calculated using equation:

$$F_{hv} = \sum_{i=1}^{c} [\det(F_i)]^{1/2} \qquad (10)$$

where F_i is a fuzzy covariance matrix.

5. RESULTS

The modelling and prediction of the yield is very challenging due to the long residence times and non-linearities. The yield profiles for two different cooking processes, conventional and Downflow Lo-Solids, are constructed using Gustafson's model. Both softwood and hardwood cases are presented. Softwood case is more accurate, due to reason that Gustafson's model is originally developed for softwood. The yields are calculated using equations of lignin and carbohydrates dissolution 1-6.

In Fig. 4, the lignin content profile in the conventional cooking process is shown.

Carbohydrate content profile for conventional cooking process is shown in Fig. 5. The lignin and

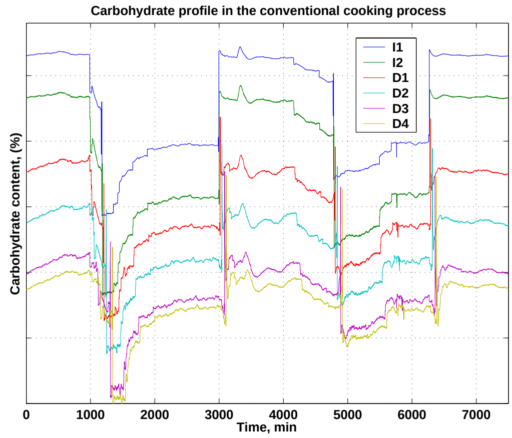

Fig. 5. Carbohydrate content profile in conventional cooking process.

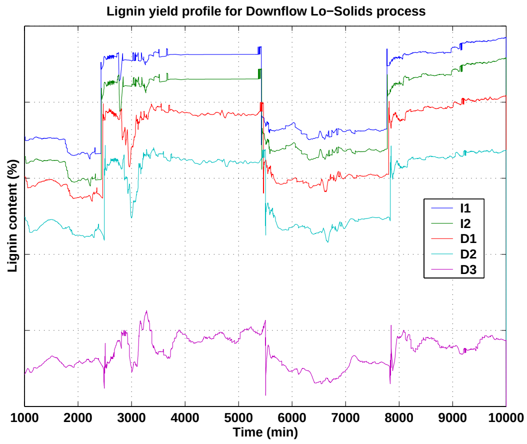

Fig. 6. Lignin content profile for Downflow Lo-Solids cooking process.

carbohydrates content calculations for the conventional cooking process are implemented into the plant's automation system.

Lignin and carbohydrates yield profiles for Downflow Lo-Solids cooking process are shown in Figs. 6 and 7.

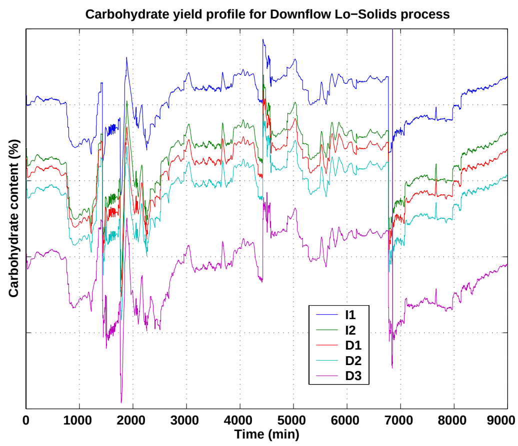

Fig. 7. Carbohydrate content profile for Downflow Lo-Solids cooking process.

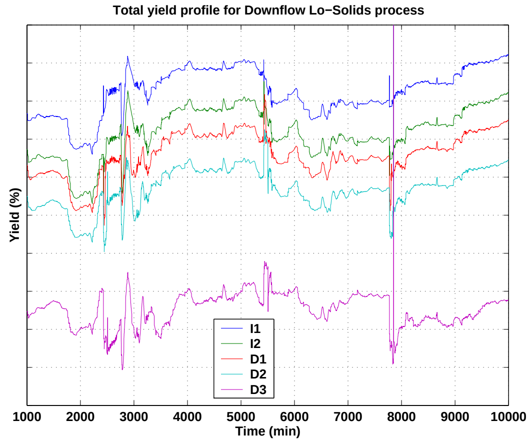

Fig. 8. Total yield profile for Downflow Lo-Solids cooking process.

The total yield profile for Downflow Lo-Solids cooking process is shown in Fig. 8.

The yield profiles are pictorial and give new information for the operators. The hardwood case is not so realistic in the carbohydrate yields, because the model is originally developed for the softwood. The lignin yield parameters are modified for the hardwood case in the earlier study (Rantanen *et al.*, 2003). In the future, the carbohydrate model parameters will be also optimized for the hardwood case.

The total yield was predicted in the conventional cooking process. The prediction point was after the impregnation vessel (zone I2 in Fig. 1). Identification data (about 50 000 data points) is collected from the industrial digester and validation data is from the same industrial digester, but from different time periods. The models are constructed using Gustafson-Kessel fuzzy clustering model. The number of the clusters is decided using the method presented in (Gath and Geva, 1989). 4 clusters were used. In Figs. 9 and 10, the modelling results are plotted by taking into account the residence time. The quality and quantity of the yield is shown in Figs. 9 and 10 using color codes as in (Ahvenlampi and Kortela, 2005). The green color indicates good yield (quality and quantity), yellow slightly reduced yield and red color very poor yield. The scales in Figs. 9 and 10 are the same. Thus it can be seen that in the validation period 2 (Fig. 10) the quality is good all the time, but in the validation period 1 (Fig. 9) there is also reduced yield (yellow) and poor yield (red). The prediction of the yield is quite accurate and it can be used as a key factor of the production.

6. CONCLUSIONS

Yield profiles are not measured in the industrial digesters. In this study, yield profiles for two

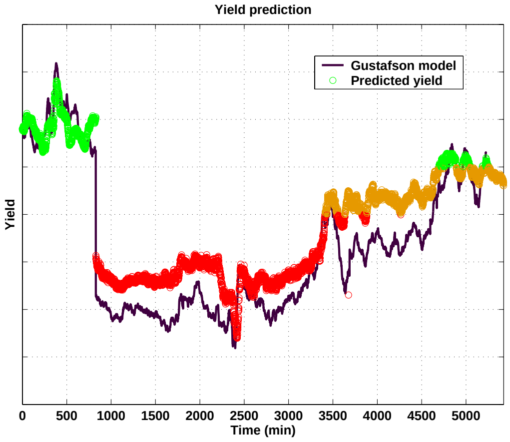

Fig. 9. Yield prediction in validation period 1.

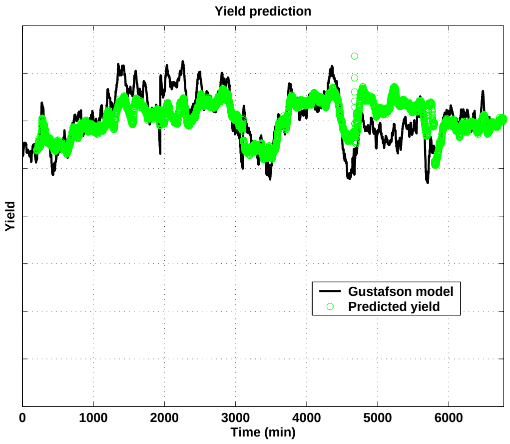

Fig. 10. Yield prediction in validation period 2.

industrial continuous cooking processes (conventional and Downflow Lo-Solids) are constructed. The yield profiles are implemented into the automation system of conventional cooking process. The total yield is predicted for the conventional cooking process. The constructed profiles give new information for the operators.

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