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. Copyright © IFAC2005

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 (Bezek 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. Temperatures are measured from the liquor circulations and from the heated steam at the top of the digester. 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 blow-line is based on the temperature of cooking circulation.

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 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 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
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 have been modified experimentally, so that the lignin intake values from the wood approximately obeys the values reported in the literature.

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:

$$\frac{\partial L}{\partial t} = k_{bc} \left[ OH^- \right]^{0.7} L,$$

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

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:

$$\frac{\partial C}{\partial t} = k_{rc} \left[ OH^- \right].$$

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

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

<table>
<thead>
<tr>
<th>Phase</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>$k_{il}$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$k_{ilc}$</td>
<td>2.53</td>
</tr>
<tr>
<td>Bulk</td>
<td>$k_{bl}$</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>$k_{blc}$</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>$k_{bc}$</td>
<td>0.47</td>
</tr>
<tr>
<td>Residual</td>
<td>$k_{rl}$</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>$k_{rc}$</td>
<td>2.19</td>
</tr>
</tbody>
</table>

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)

The 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:

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

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),

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

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:

$$ D_{ik,Bi}^2 = (z_k - c_i)^T B_i (z_k - c_i), \quad (9) $$

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:

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

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 L-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
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.

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
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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