Model predictive control of the chip level in a continuous pulp digester, a case study

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Abstract: This paper describes the digester chip level control problem and shows a MPC system implementation for the level control.

The objective with implemented chip level control system is to stabilize the transport conditions in the bottom of the digester by using the chip feed and not the blow flow as the primary manipulated variable. The results indicate a smoother digester operation and a reduction of the kappa number variations compared with the original control system.

The continuous digester (The Kamyr digester) is a complex tubular reactor where the delignification of the wood chips takes place through combined chemical treatment and thermal effects. The digester consists of three important zones: the impregnation zone, the cooking zone (delignification reaction) and the washing zone where the counter flow of the bottom dilution flow slows down the reaction and removes residual chemicals and lignin. The key parameter for monitoring the digester system performance is the kappa number, which represents the residual lignin in the pulp.

The kappa number is influenced by the following variables, Svanholm [5], Lundqvist [10]:
- Chip quality (humidity, mixture, species, size, etc.)
- The quantity of Effective Alkali (EA) in the chips
- The temperature that chips are exposed to
- The time the chips are exposed to EA and temperature (the time in the delignification process)

The statements above are valid when looking at the delignification process at the chip scale, but it is very important to also consider how the variables above are behaving when the chips are transported through the digester process (the digester scale). It is important to understand the general sequence of transport and reaction processes that govern the overall digester operation. Stable transport conditions at every subpart in the digester system are essential for having good conditions for the chemical and thermal treatment of the chips. The kappa number variability is related to variations in chip retention time in the digester, caused by fluctuations in chip packing, blow line consistency, etc. These variations can be, to some extent, detected by measurements of chip level, blow line differential pressure, and bottom scraper amperage.

In this paper a number of reports on digester chip level control have been analysed regarding the control strategy and controller structure. A chip level control strategy (two-vessel Kamyr digester) is proposed, aiming to stabilize digester bottom conditions. The strategy is implemented as a MPC controller scheme and as a PID-solution in DCS.

The MPC scheme is straightforward regarding the handling of constraint variables in the control problem. By combining the controlled and constraint variables, it is possible to set up and tune the MPC controller both to control the level to a set point and to have upper and lower limits to ensure the production level, i.e. to keep the chip level at an average value (set point) but at the same time allow the level to fluctuate within certain limits (as a buffering functionality). The MPC controller is implemented on a continuous digester at the M-real Husum mill, Sweden and has been running since the end of 2003. The digester operators state that digester system has operated more smoothly during this winter period with the updated level control system, compared to last year’s operation.

Another purpose of this work is to implement a multivariable model-based controller, such as a MPC controller, on a selected pulp and paper process. The selected process (the digester system) and the MPC controller will be used as a test system for the development of a monitoring and diagnosis system for multivariable and multi-loop control systems.

THE CHIP LEVEL CONTROL PROBLEM

The primary objective of using a digester supervisory control system is to minimize the variation in the kappa number and to improve (stabilize) digester operation. The chip level control has an important effect on that objective. It is important to understand how the variations in the chip level itself are influencing the chip cooking process, and also how the manipulated variables, used for controlling the level, are influencing the digester process.

A number of papers have been written regarding the control of the Kamyr digester chip level. The following section is an attempt to review the control strategies, controller structures, Manipulated Variable (MV) and Controlled Variable (CV) selection, etc., described in those papers.

Fiber discharge rate as MV
- Sastry [12] designed a Self Tuning Regulator (STR) which used the blow flow as the primary MV. The chip flow and bottom scraper speed
were used to deal with extreme level conditions. No primary control of the blow line consistency was presented. The results showed a decrease in chip and black liquor flow variations to the digester by manipulating blow flow compared to the original control system. According to Belanger et al. [9] this control system was abandoned because of bad reliability of the STR, but Belanger mentioned nothing about any problems with the selected control strategy.

- Belanger et al. [9] made a comparison between using the blow flow and the digester bottom scraper as the primary manipulated variable for the chip level control (using a STR control structure). The two alternatives showed similar results regarding top separator amperage (level measurement) variations but the digester bottom scraper (outlet device) was selected because of different practical reasons. The operators also preferred the bottom scraper as the primary MV because of the more steady blow flow. Controlling dilution flow, where the set point was ratioed to the scraper set point, aimed to stabilize the blow flow consistency. The dilution controller output was slowly changing the blow flow set point. The STR controller increased the stability of the production.

- Allison et al. [7] designed an adaptive controller based on a generalized predictive control structure (GPC). The blow flow was used as the primary manipulated variable. No clear motive was presented regarding why the blow flow was selected. The blow flow set point is set by the GPC together with the production feed forward signal and a proportional feedback signal from the digester top separator current. No primary control of the blow line consistency was presented. The adaptive controller showed improvement of the chip level control by means of a closer mean value to level target and a reduction of the standard deviation of the chip level signal.

Chip feed rate and fibre discharge rate as MV

- Fuchs et al. [13] used the chip metering speed as the primary manipulated variable for the chip level control. They pointed out that it is important to have a stable fibre discharge rate in order to stabilize the residence time in the cooking zones of the digester. The manipulations of the blow flow were minimized, but a very slow feed-forward signal was added to the fibre discharge target (blow flow target) based on the difference between the nominal production and the actual production i.e. the chip meter speed. Manipulating the digester bottom scraper, with some correction of the bottom dilution flow when the scraper speed was at its limits, primarily controlled the blow line consistency. No specific results were shown regarding the level control performance.

- Al-Shaikh et al. [11] presented a control strategy where the chip meter speed was used as the primary manipulated variable for short-term level variations, and the blow flow ratio, for long term variations. The chip meter speed sets the production target, with a limited bias added for the level control. When the accumulated error for the chip meter speed (from the nominal production speed) exceeds a certain limit the blow flow ratio target is adjusted to maintain target production. The blow line consistency was not directly controlled.

- Allison et al. [6] used both the chip meter speed and the blow flow as manipulated variables. The chip meter and the blow flow simultaneously reacted to level disturbances, but with the chip meter slowly returning to steady state production rate and with blow flow to compensate for the persistent load disturbance. The GPC was set to constrain the chip meter speed about the production target speed. The motive for the use of the chip meter was to reduce blow flow manipulations. No specifications about blow line consistency control were described.

Discussions with operating personnel indicate that large blow flow manipulations could disturb the chip column movement and change the mass and energy balances. The results showed a decrease of 50% in blow flow manipulations, but the expected improvements in pulp quality were not achieved (a slight increase in kappa variations). The MIMO GPC controller was disabled after six months of operation. According to Allison et al. [6] the bad chip level measurement (strain gauge measurement) and the fact that the mill had been experimenting with a number of new grades were contributing factors to why the GPC was switched off.

- Lundqvist [10] presents a chip level control strategy that utilizes both the chip meter speed and the blow flow as manipulated variables depending on the size of the chip density variations. At small chip density and wood property variations, the chip meter is used as primary MV and the blow flow is kept constant. If the chip density varies considerably, the blow flow is used as MV and the chip meter is kept constant. The tuning of the mix of the two MV’s should be done regarding the chip level response characteristics and with the kappa number chosen as the control performance criterion.

- Amirithalingam et al. [2,3] discussed how chip level control relates to pulp quality parameters such as the kappa number. They proposed that the manipulated variable for the chip level control should be selected according to the origin of the disturbance, e.g. if a change in the digester chip level is caused by a change in chip bulk density, the right action would be to change the chip metering speed. However if a disturbance in the chip level were caused by a change in the fibre discharge rate (change in blow line pulp consistency), the right action would be to change the blow flow (or digester
The fluctuation of the chip pile may cause changes in the driving force and furthermore variations in the chip column movement and compaction. The chip column is, however, elastic and compressible and the elasticity of the column may be reversible or irreversible [8] and the compaction degree of the chip column may fluctuate.

If the chip column is moving quite freely through the digester, the residence time in the impregnation, cooking and washing zones depends mainly on the fiber discharge rate [13]. It is then important that the fibre discharge rate is stabilized. Amirthalingam et al [2] pointed out that a good chip level controller structure should react to the root cause of the level disturbance.

The choice of control philosophy (selection of MV’s and CV’s, controller structure etc.) for the chip level control may be more important than actually achieving a very tight control of the level [2].

The proposed control strategy above is mainly implemented as a Model Predictive Control scheme on a stand alone PC communicating via an OPC link to the Siemens DCS system. A watchdog function for the OPC link checks that the communication is established and running. If the communication is disrupted, a back-up control function is implemented in the DCS system with mainly the same control strategy as the MPC implementation.

### Implemented control strategy

A system structure of the implemented control strategy is shown in Figs. 2 and 3. The digester chip level is controlled by:

- Manipulating the impregnation vessel bottom scraper and the bottom dilution flow.
- The dilution flow (sluice) is used as the primary manipulating variable to maintain the level close to target.
- The scraper speed is used to maintain the level within an upper and lower limit. When the level is within these limits no action is made by the scraper. (MPC constraint functionality, see below)
- The scraper speed is slowly moved to a minimum speed target to move the average control action to the bottom dilution flow and to prevent too high scraper speed.

### PROCESS CONTROL

The continuous digester at M-real Husum mill is a conventional Kamyr digester system, Fig.1, which consists of an impregnation vessel and a steam/liquor phase digester. The digester has four liquor circulation flows (C5, C6, C7, and C8) where the C7 is not used and the C6 trim circulation is only used for alkali measurement. The alkali is added in the impregnation vessel and in the C5 and C8 circulation.

The production rate is about 1000 tons/day (softwood) and the kappa number target is 30. The digester supervisory control system at M-real Husum mill consists of following modules:

1. Production rate change control
2. Pre-steaming
3. Chip level control of digester and impregnation vessel (Blow flow, gamma source as level ind.)
4. Wood/liquor ratio and circulation flow control
5. Pulp consistency and sluice flow control
6. White liquor addition (concentration) control
7. H-factor control
8. Kappa number prediction and feedback control

All control modules are implemented in the Siemens DCS system (mainly with PID controllers). The actual production load on the digester is about 50% higher than design figures, production per bottom square meter [ton/m²*day]. During the cold wintertime, snow, ice and frozen chips make it more difficult to get a smooth digester operation compared to summertime.

### Process analysis

The chip level gives an indication of the chip column movement and the residence time (the extent of the chemical and thermal treatment) for the wood chips in the digester.

The downward movement of the chip column is due to the gravitational force, which mainly depends on the height of the chip pile (bulk density, etc) that is above the liquor level and the density difference between the chips and the liquid. The digester chip level is controlled by:

- Manipulating the speed of the chip metering wheel. The control signal is added as a production bias to the nominal production with upper and lower limits (+/- 2 t/h).
- Manipulating the digester bottom scraper controls the pulp blow consistency. The pulp consistency measurement is primarily based on the differential pressure between digester bottom and blow line. The in-line pulp consistency measurement device (yield stress) and the function the bottom scraper may be used to adjust the pulp consistency controller.
- The blow flow is manipulated slowly to move the actual production back to target production.
- Depending on the performance of the pulp consistency controller the dilution flow could be used to improve consistency control.

The impregnation vessel chip level (controlled variable) is controlled to the level target by adjusting the set point for the bottom dilution flow (FC5.2 in Fig. 2).
The impregnation vessel chip level is also set up as a constraint variable with an upper and lower limit. If a violation of these limits is detected, the bottom scraper will react powerfully, together with the dilution flow, to bring the level within the limits again. When the level is within the limits, the scraper speed is slowly brought back to a target speed to move more of the average control action onto the dilution flow (FC5.2). The impregnation vessel scraper speed is both a manipulated variable and a control variable in the MPC controller, Table II.

The constraint variable can be seen, in this case, as a safety function to prevent plugging of the impregnation vessel. That allows a smoother control action for the set-point control. It is not very critical to have a tight level control of the impregnation vessel, and that also gives the possibility of using the impregnation vessel as a buffer for chip feed variations into the digester system.

**Step response modeling and MPC controller design**

A key element in the design of the MPC controller is the dynamic process model, which is used for the output predictions and to relate the MV’s to the CV’s. The data used for the modelling and design has been generated by step response experiments. The possibilities of using more sophisticated data generation tools like PRBS signals were limited. Figures 4 through 6 show the step responses for the chip levels and the differential pressure.

The step response figures show that the digester and impregnation vessel level process can be characterized as an integrator process with a time delay at the input. The time delay is, however, longer than physically expected. That could be explained by the time it takes to accelerate the chip column in the impregnation vessel and the compaction of the chip column in the digester due to chip column elasticity [8]. The chip column elasticity can possibly be modelled as a second order system. An integrating process with dead time was selected as the model structure for the models needed in the MPC design, except for the differential pressure control, where a first order model structure was used.

**RESULTS AND DISCUSSION**

The MPC controller has been running since start-up in mid December 2003. The back up level control system in the Siemens DCS system was installed in August 2003 and was running until the MPC controller was installed. The original digester level control system, with the blow flow as the primary manipulated variable, is still available for the operators but has not been in operation since the start-up of the new level control strategy.

Table III shows some figures regarding the standard deviation for the chip meter speed [rpm], blow flow [m³/h], kappa number, digester chip level [m] and pulp consistency [%]. The standard deviation calculations are made from periods of equal length and similar production rates.
The results show a clear reduction of blow flow manipulations and pulp consistency variations. The reasons for the reduction in kappa number variations may need a closer investigation of the overall production conditions. The digester operators’ confidence for the new control system is high and they state that the digester operation has been smoother this winter period than previous ones.

Figure 7 shows a trend plot of the digester level control. The production bias (chip meter speed) is manipulated to control the digester level. The blow flow set point is adjusted at time 16:48 when the production bias is outside the +/- 1 t/h control limits.

Figure 8 shows how the blow line pulp consistency is controlled by manipulating the digester bottom scraper speed. The goal is to keep the pulp consistency within +/- 0.25%. The digester bottom dilution flow may need to be involved in the pulp consistency control function to improve control performance [13].

The MPC controller implementation has improved the control of the impregnation vessel chip level. With the constraint functionality in the MPC scheme it has been possible to combine disturbances reduction with safety function control in the same control algorithm.

The future work regarding the level control system will be to:
- Modify and improve the control function for the blow flow and implement that function into the MPC controller
- Improve the pulp consistency control by utilizing dilution flow and bottom scraper motor amperage.
- Utilize gain scheduling for improved tuning at low production rates
- Start-up of the digester and MPC controller performance monitoring project.

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**LITERATURE**
3. AMIRTHALINGAM, R., LEE, J. H. Subspace Identification Based Inferential

Résumé: La présente communication décrit le problème du contrôle du niveau des copeaux dans le lessiveur et illustre la mise en œuvre d'un système MPC pour le contrôle du niveau. Le but de ce système est de stabiliser les conditions du transport au fond du lessiveur à l'aide de l'alimentation des copeaux et non par le soufflage comme variable de commande principale. Les résultats ont été d'un meilleur fonctionnement du lessiveur et d'une réduction des variations de l'indice Kappa par rapport au système de contrôle initial.


Keywords: PROCESS CONTROL, CONTROL SYSTEM, CHIPS, CONTINUOUS PROCESS, CHEMICAL PULPING, FEEDERS, DIGESTERS.