APPLICATIONS OF SIMULATION MODELS FOR DIAGNOSTICS AND MODEL BASED CONTROL IN PULP AND PAPER AND POWER PLANT APPLICATIONS.

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Abstract: Dynamic process models have been produced for bubbling bed combustors, circulating fluidized beds and pulp digesters. The models were made in Modellica and thereafter transferred as objects into Mathlab/Simulink, with OPC link to the process computer system via the data-base. In the application at a pulp mill the model also has been combined with a NIR measurement on ingoing wood chips, to determine the reactivity of the wood as a function of residence time, chemical additions and temperature. Later on the NIR will be used as feed forward for both model based control and for diagnostic purposes with respect to channeling and hang-ups. In the power plant applications models have been used for dynamic data reconciliation for a CFB boiler and for MPC-control using NIR for moisture measurements of ingoing bio-fuel to a BFB-boiler. The applications will be presented at the conference.

1. Introduction

Mathematical simulation models can be used for many different applications. In this paper we will describe some applications that have been implemented at power plants and pulp and paper industries during the last year. The models have been developed in Modellica, a modeling language suitable for making dynamic models, but where it is also easy to get initial conditions to start with. It is otherwise difficult and time consuming to tune a large dynamic model to achieve a stable starting situation. The models include the functionality needed for the actual application.

Models have been used earlier for different applications, like Mercangöz and Doyle [2006] for plant-wide optimization of a pulp mill process and Morari [2007] have a software for MPC that can be down loaded from his web-page for use by ”any one”. In our case we have principally used such an MPC, but tuned it towards the simulator. The simulator on the other hand was calibrated towards the real process, to verify that the dynamics were correct. Finally we also made tests with the MPC building tool directly towards the process, to fine tune. In a second application of a similar character we believe there will be no need for this last step.

Laperrière and Wasik [2002] Implemented optimization with process simulation for P&P applications and Pettersson et al [2006] used a simplified model for a complete cross recovery mill to give the production a decision support for pulp mill operations based on large-scale on-line optimization. This now has been in full scale operations for several years at Billerud Gruvön mill. Suojärvi and Tienari [2006] used a Simulink model together with simulated annealing for off-line optimization and production scheduling of TMP production. Hess [2000] used also a gPROMS model for optimization and scheduling of a chemical process (Activated carbon production). Bell et al [2004] have described operations decision support based on dynamic simulation and optimization. Dahlquist [2008] has given a number of references in a review article about applications of Process simulation in pulp and paper industry.

Description of the models:

Pulp and paper

The first example will be a pulp application. A model has been developed for a continuous pulp digester. This has been implemented at a SAPPI mill in South Africa on-line in September 2008, and is being implemented right now at Korsnäs mill in Gävle. The models for the two plants are principally the same, although the reaction constants vary as the wood used is quite different. Also the circulation loops differ between the two digesters, where the one in South Africa is a gas-phase digester while the one at Korsnäs is Hydraulic. Still, from a modeling point of view this is not that important. A basic model block has been designed where the chemical reactions appear as a function of the temperature, concentration of chemicals, residence time and wood quality. In the impregnation step before the actual cook additional reactions take place. These reactions are wetting first and then exothermal reactions splitting off water.

The reactions in the digester are principally the same as has been described in e.g. the Purdue model by Christensen [1982]. The dissolution of lignin (fast and slow) and hemi-cellulose (L(i)) is expressed by

$$dL(i)/dt = \text{reactivity\_const}*[OH^-]^{0.5}[HS^-]^{0.5}*\exp(A-B/T) \qquad (1)$$

The reactivity constant includes both actual reactivity and effects of chip size and the diffusion related to this. The constants A and B are determined for each specific wood quality and show the temperature effect on the dissolution rate. The hydroxide and sulfide concentration effects are just taken from literature and are kind of an average of what different sources are using.

The model also includes simple fluid dynamics as we build the digester from a number of blocks. These can be linked together both in vertical and horizontal direction. Each block is then having a compression factor that is the inverse to the amount of lignin remaining in the wood chip. That is we assume that when the lignin is dissolved the wood structure collapses and the wood chip is deformed by pressure. Therefore the flow resistance increases as the chips pass down through the digester and lignin is dissolved. If we introduce e.g. channeling in one block we also decrease the flow resistance in this block. At the same time we make a reduction of the reactivity constant for the wood chips in this block. This is given an opportunity to test the effect of channeling at different positions in a digester.

Flow of wood chips is normally constant with respect to mass flow on the way downwards through the digester. If we want to see the effect of hang-ups we reduce the chip-flow in the actual block.

We also have configured blocks in such a way that a block can have flows from all attached blocks. If there is a wall, the flow is set to zero. If there is a screen the flow through the screen is normally set as a set point, although it can be influenced by adding a valve after the screen. If the screen is being clogged, this is seen as a reduced valve opening.

The flow through each block is principally given by introducing “fake valves” in all directions of a block. The resistance is then half the actual block + half of the neighboring block. By solving a pressure –flow system for all blocks we determine the flows. To get the chemical reactions we then implement these flows into a parallel model with the same configuration, but where the chemical reactions are included, but without the flow resistance. The dissolution of lignin is giving the remaining lignin concentration, and thereby we get the value of the compression for the next time step in the block.

In a simplified version of the model we only use predefined flow rates through the digester, where the actual change of inflows just changes the flow in a specific block in proportion to the change of the external flow – feed or screen flow.

The model is tuned by measuring remaining alkali and dissolved lignin in the extraction as well as the kappa number of the fibers at the blow-line. As we also know the temperature and additions of chemicals we can make a balance for a specific batch of fibers, e.g 2 or 5 or 10 tons. In Korsnäs we also measure the NIR spectra of incoming wood chips and correlate these spectra to the reactivity of a specific batch of wood. Tuning of NIR spectra to the other measurements has just started, so we don´t have the correlation for that many different wood variants yet. Still, the intention is to use the information from the NIR meter for feed forward control as well as for diagnostics later on. For the time being we make an assumption from what wood specie that is introduced like 10% spruce + 90% pine or 20 % hard wood + 80% softwood etc. As wood becomes more costly, the quality variance may be significantly higher in the future and then a more precise measurement of the quality may be needed, to optimize the production. The possibilities with NIR for wood property determination is described in Axrup et al [2000]. The use of NIR for moisture determination is described in Dahlquist et al [2005].

2. Power plant applications

At Eskilstuna Power plant we have one larger BFB boiler (110 MW) and a smaller CFB boiler. For the larger BFB boiler we have made a simulation model that has been used to tune an MPC controller from ABB. The actual model has been made in Modellica and contains three major inventories: the boiler gas + particles, the steam drum and steam-water system and the recirculation channel. The latter is added as the bed control is affected quite a lot by the recirculation of exhaust gas.

The mass change by time , $\frac{\partial m}{\partial t}$, is given by:

$$\frac{\partial m}{\partial t} = \sum_{i=1}^{i=n} \dot{m}_{in}(i) - \sum_{i=1}^{i=n} \dot{m}_{ut}(i) \qquad (2)$$

Here $\dot{m}_{in}$ (i) is the flow in to a volume element for each component, *i* and $\dot{m}_{ut}$ (i) is the corresponding flow out.

The change in concentration for each component *i* is given by:

$$\frac{\partial c,i}{\partial t} = \frac{\left(\sum ci \cdot \dot{m}_{j,in} \cdot \sum ci \cdot \dot{m}_{k,ut}\right)}{m_{inventory}} \qquad (3)$$

Here $\frac{\partial c,i}{\partial t}$ is the change in concentration for each component with respect to time, c,i , is the concentration for each component , *i*. $\dot{m}_i$, is the mass flow to the inventory $m_{inventory}$ and $\dot{m}_{k,ut}$ are the out flows from the inventory.

The temperature in each inventory is given by:

$$\frac{\partial T}{\partial t} = \frac{\left(\sum T_j \cdot \dot{m}_{j,in} - \sum T_k \cdot c_i \cdot \dot{m}_{k,ut}\right) + \Delta H - U \cdot A \cdot \left(T_{block} - T_{utsida}\right)}{m_{block} \cdot \left(\sum c_i \cdot cp_i\right)} \qquad (4)$$

Here ΔH is the energy released during combustion or other reactions, *U*, is the heat transfer number, *A*, is the area of the heat exchanger and T_{utsida}, the temperature at the other side of the heat exchanger tubes.

The goal with the control strategy is to decrease the variations in bed temperature.

The multivariable MPC-controller is configured to control the bed temperature, the exhaust gas moisture content and the total gas flow through the bed, by controlling the 1) exhaust gas recirculation flow (the set point), moisture content of the air (set point of humidification) and the primary air flow (set point). A number of feed forward signals can be used as well as some feed-back signals, giving information about the performance of the boiler. One important FF signal is the moisture content of the incoming bio fuel. This is measured on-line using a NIR-spectrophotometer that has been calibrated towards moisture content of many different types of bio-mass fuels. The only difficulty here is that it takes some 30 minutes before the fuel comes from the meter position to the boiler. This gives some uncertainty, but also gives a possibility to take proper actions before it is too late. In worst case we can actually redirect the fuel if it is too wet. Another signal of interest is the soot-blowing. During soot blowing the moisture content goes up, but should not be addressed in the control, as it does not affect the bed temperature. The reason for otherwise controlling the exhaust gas moisture is as heat is recovered in an exhaust gas condenser to produce hot water for district heating.

The model for the MPC controller has been made by process identification. In this case we have been making first a coarse tuning towards the Modellica model. Thereafter we made disturbance experiments. These both have been used to calibrate the process model and to fine tune the MPC-model. Later on the goal is to make the Modellica model good enough to use for most of the tuning of the MPC-controller in a second installation, to reduce the need for disturbance experiments to a minimum. The experiments have been done based on excitation with signals of the type PRBS (Pseudo Random Binary Sequence). In the controller used from ABB there is a tool to make a systematic variation of several signals simultaneously to avoid correlation between the signals. An example of this type of experiments is shown in Figure 1. Later on more experiments have been performed.

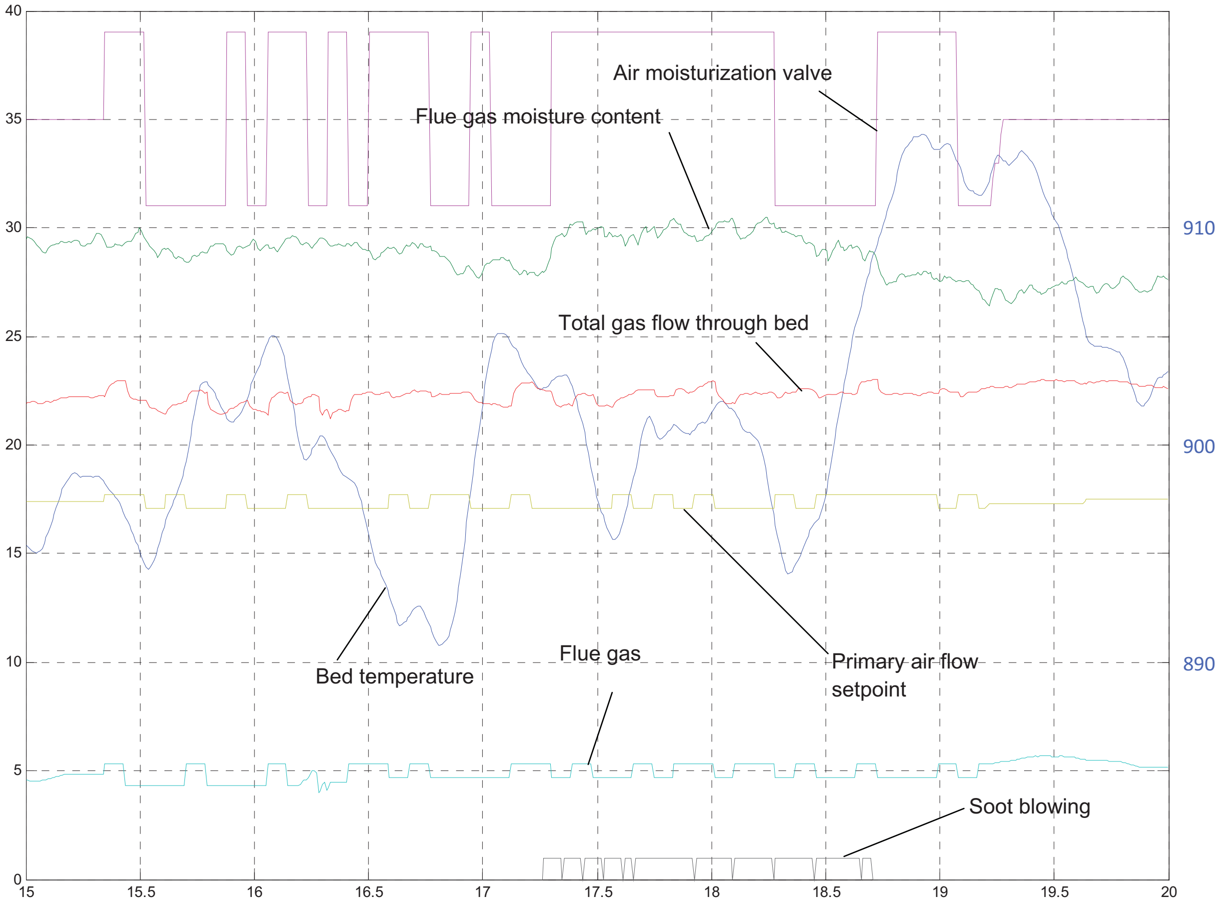

Figure 1. Log data from identification experiment with uncorrelated PRBS excitation. From the top: Violet curve position of humidification valve; dark green moisture content in exhaust gas; red curve total gas flow through the bed; blue curve is bed temperature; yellow- green set point for primary air; light blue set point for exhaust gas recirculation and black at the bottom soot blowing flow.

With the model the controller has been tuned to get a robust control of the bed temperature to the value given by the operator. The fine tuning has been performed by varying primarily the exhaust gas recirculation flow rate, and with a slower adjustment of the primary air flow. The operator selects the average value of the total flow through the boiler, and the controller then keeps it within a given set of limits. If e.g. 23 Nm^3/s has been selected, the controller has kept the flow rate between 22 and 24 Nm^3/s. It is when we come close to any of these limits that the primary air flow is coming into the control more noticeable. The behavior is seen in figure 8 that is a log from the first time the controller was operating actively on-line.

3. Results:

Pulp Application

What we can see from the pulp model predictions is how e.g. the kappa number and the residual alkali react as a function of a change in cook temperature. This is seen in figure 2. This information then has been used to fit experimental data and the constants in the model, so that the model then has been able to be used for different type of predictions. One thing is to predict channeling, which is seen in figure 3.

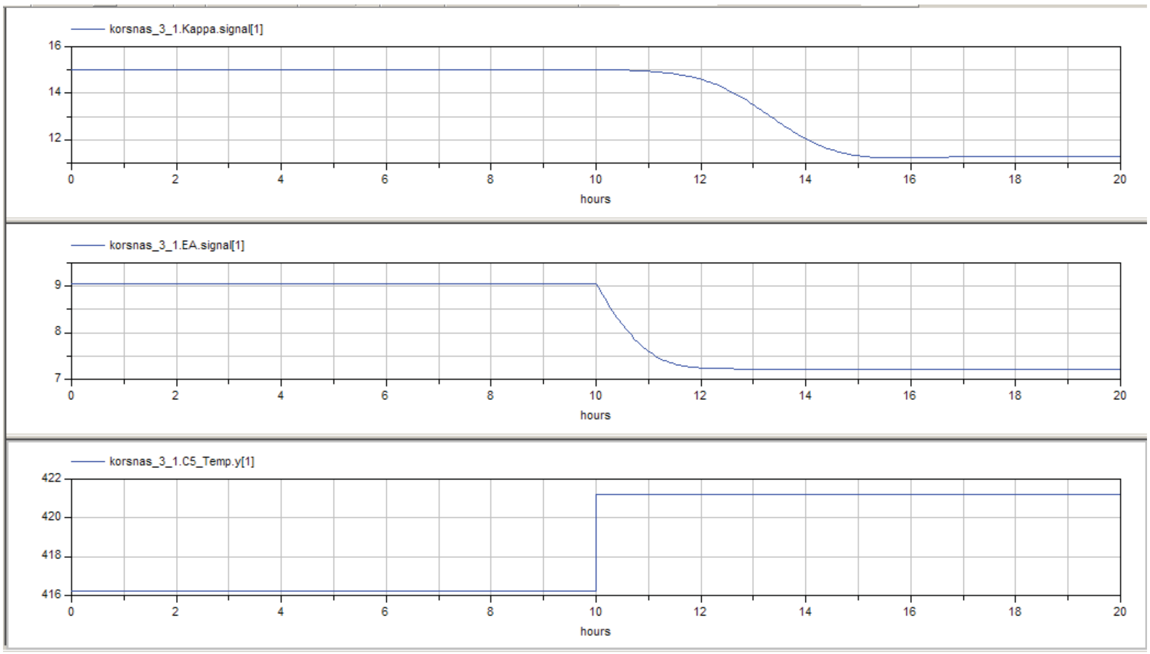

Figure 2. The effect of a temperature change (bottom) in the digester on kappa number (top) and residual free alkali in the extraction liquor (middle diagram). Results from simulation.

What we can see is that the free alkali (EA) reacts much faster than the kappa number. The reason is that the kappa number relates to how fast the wood chips are moving downwards through the digester, while the free alkali is effected directly as the liquor only has a short distance to travel from injection to screen.

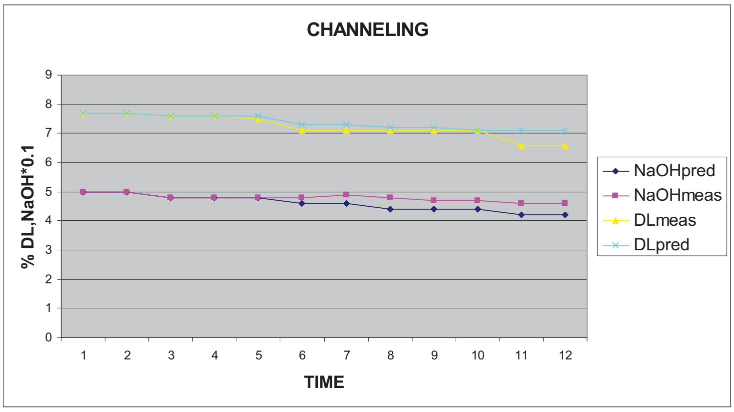

Figure 3 Channeling can be predicted by comparing real measurements of residual alkali (NaOH) and dissolved lignin (DL) in the extraction line. The model is used to calculate what the value ought to be depending on the wood properties, temperature and chemical additions during the cook. Results from simulation.

In figure 3 we see that the predicted value of NaOH in the extraction line is lower than the measured value. This indicates that the liquid has not been affected as predicted by contact with wood chips, and thus less has been consumed than expected. Due to channeling less lignin has been dissolved, and thus the dissolved lignin that is measured in the extraction line is lower than the predicted value. Also here we are using the model to calculate what values could be expected for a given wood property and given conditions.

Power plant application

It is not as easy as you would like it to be to identify how much better a new controller performance in comparison to before it was installed. In this application we have first installed the moisture content meter of the incoming fuel. As this was installed the operators got a tool to start mixing the fuel to minimize the variations of fuel into the boiler. This has also influenced the bed temperature stability as seen in figure 4. The blue curve is for 2006, before the moisture measurement was installed. The green curve is for 2007 when it was in operations. We can see that the temperature variation has gone down. During autumn 2008 we then installed also the MPC-control. We have not got that much concrete data analyzed yet, but the operators and production manager is giving the feed-back that the controller is working well and that they now can control the bed in a better way. During December 2008 we also got more varying moisture content of the fuel, and then it became more evident.

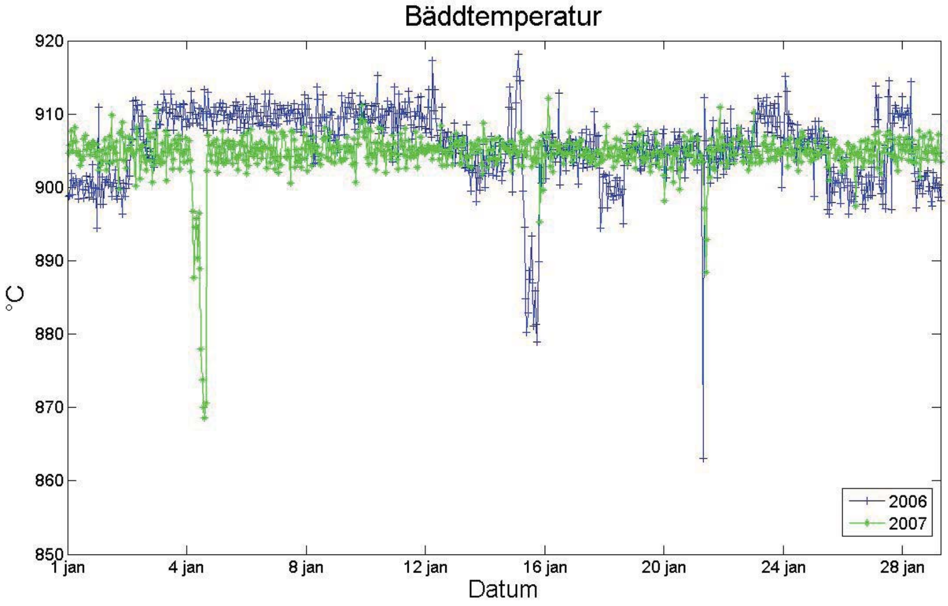

Figure 4 Bed temperature for January 2006 (blue line) and January 2007 (green line).

Until we have had a possibility to really analyze the plant data we can see the response of different actions through the simulations using the Modellica model. In figure 5 we can see how the bed temperature is reacting to increased moisture content in the combustion air by 5 % compared to the original value. The bed temperature is then dropping by ca 1.4 °C. The full impact of the change is seen after approximately 12 minutes.

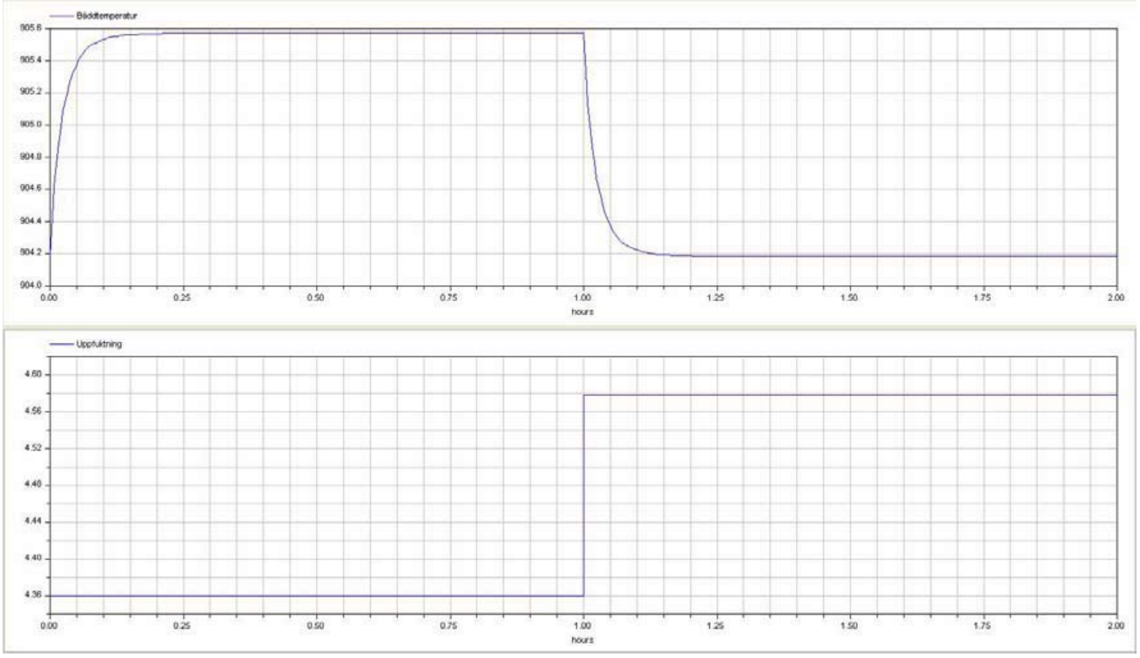

Figure 5. Increase of humidification of combustion air with 5%.

Figure 6 shows how the bed temperature is changed as the exhaust gas recirculation flow is increased by 5 %. The bed temperature is dropping by approximately 22 °C. The full impact of the change is seen after 10 minutes.

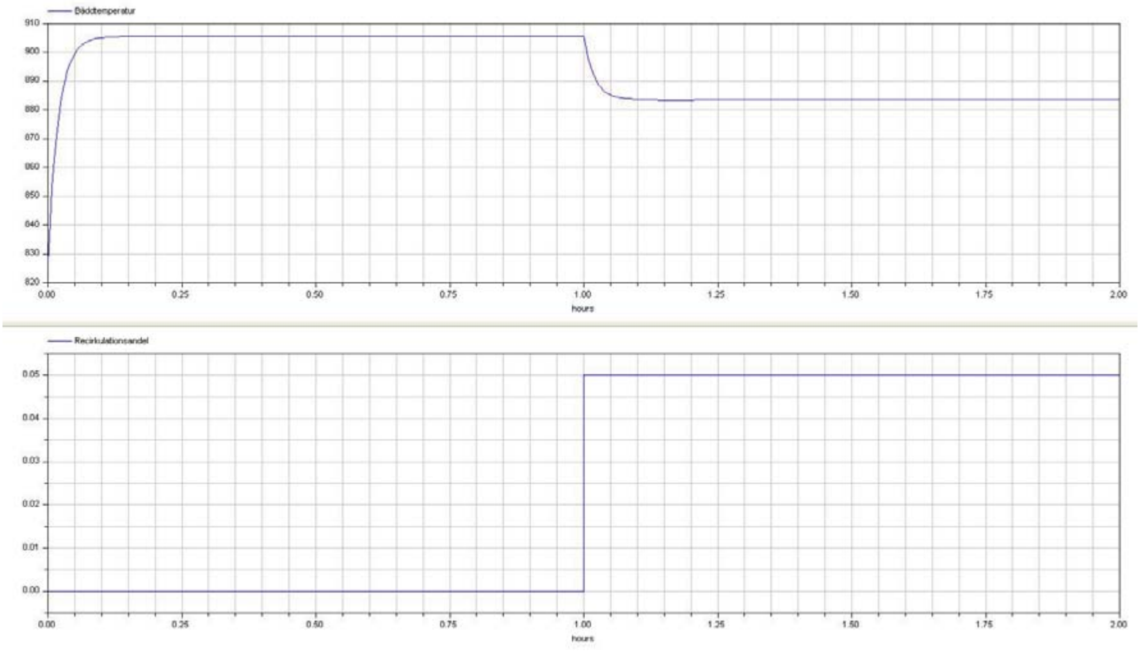

Figure 6. Increase of recirculation flow of flue gas with 5%.

As already has been mentioned the exhaust gas recirculation is giving the strongest impact and is thus the primary control variable, while the humidification is used for fine control.

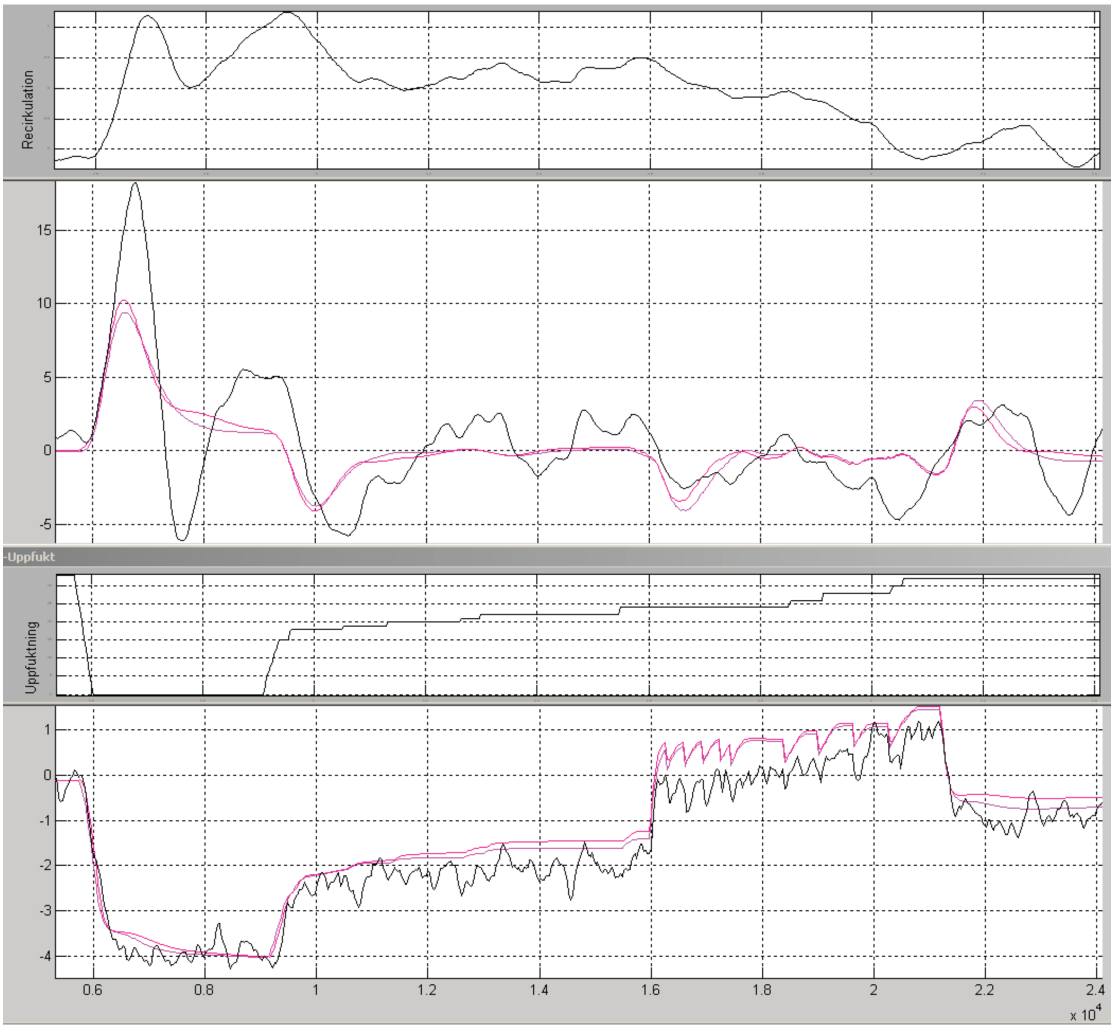

Figure 7 Variations in log data shown together with simulated model outputs (red, from two different models). Signals, from top to bottom: Flue gas recirculation, Bed temperature, Air moisturization valve, Flue gas moisture content.

The effect of different adjustments in the process variables is seen in figure 7. An evaluation of the MPC control is then shown in figure 8. Until 14:13 only exhaust gas recirculation was used for the control. Thereafter also the primary air was controlled between given upper and lower limits in relation to a set point flow. The total gas flow is the sum of the primary air flow and the exhaust gas recirculation gas flow. Here we can notice a smoother control, which shows that the effect is positive. Finally we also make a variation in the air humidification.

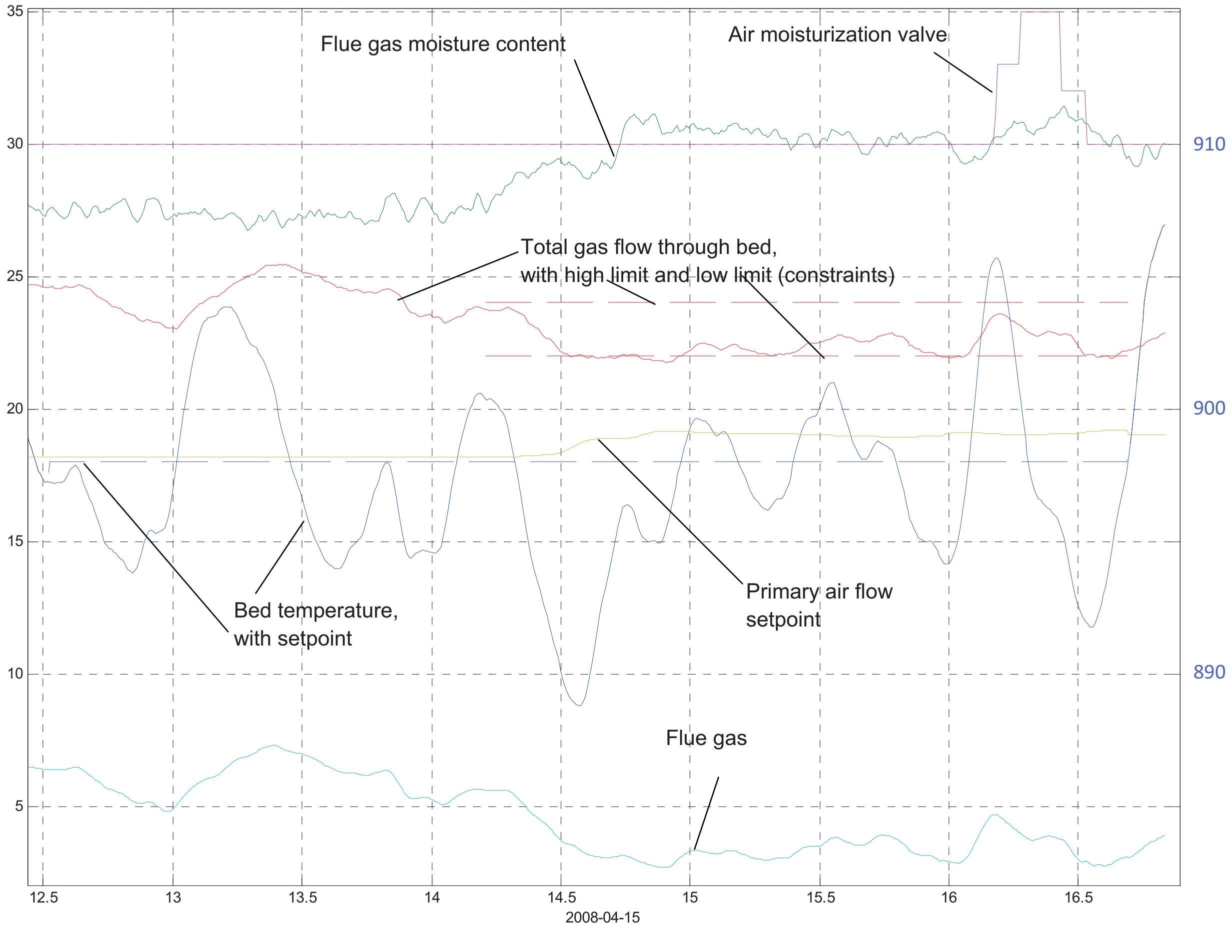

Figure 8. Evaluation of MPC controller. From the top: Violet curve position of humidification valve; dark green moisture content in exhaust gas; red curve total gas flow through the bed; blue curve is bed temperature; yellow-green set point for primary air; light blue set point for exhaust gas recirculation

4. Discussion:

Pulp application: In the case with the pulp digester we can see that we can use the model in several different ways. First it is used to correlate different variables to each other. Thereafter the model can be used to fit e.g. NIR spectra to wood properties. We are here primarily using data we know were taken when the process was operated in a good way. In an iterative way we can then update both the model accuracy as well as the prediction power of the wood quality from the NIR spectra. When we feel the model prediction power is good enough we can start predicting process abnormalities. This can be used to detect both process problems like channeling and hang ups as well as sensor problems. When we have learnt enough about the model prediction power and have concluded that the plant is operating as it should, we can start optimizing the actual production by modifying the chemical additions, flow rates and temperatures to get as high production capacity for a given final quality.

Power plant application: A MPC-controller from ABB was installed and tuned towards first a Modellica model, and then fine tuned by excitation experiments in the plant. The controller has been operating on-line since three months back and the evaluation is not yet finalized. Still we can see that different disturbances can be controlled in a better way than earlier, and the operators seem to be satisfied with the controller. There are still some adjustments needed. E.g. the effect of small adjustments in exhaust gas recirculation flow rate gives high impact when the flow is low, but minor effect when the flow is high.

Principally we can see that the moisture content of the bed is important for the stability of the bed temperature. This is seen as the bed temperature varied significantly more during 2006 (895- 905) than during 2007 (close to 905), when the fuel moisture was kept more stabile. We also can see from the evaluation of the control during autumn 2008 that the MPC-controller works well. We still have to evaluate the effect of the FF signal of the moisture content. This is being done right now, and maybe can be added before the final version of this paper.

For the air humidification the effect was assumed to be linear to water dosage, but seems to be more of the on-off type in reality! An increased flow of primary air is first reducing the bed temperature, but then an increase. The reason is probably that first the bed is cooled by the air, but then more material is combusted and thus the temperature is increased. This assumes that we have gasification in the bottom of the bed, which can be reasonable. At low moisture contents of the fuel, the effect of a variation has been lower than at higher moisture contents, which looks reasonable as well.

5. Conclusions:

What we can see is that the use of mathematical simulation models can enhance the utilization of both process data and process understanding so that improved diagnostic, control and thereby process optimization can be achieved. In the two examples we can see that similar type of model approaches can be used for quite different types of processes, like pulp digesters and power boilers. It also shows the potential of combining soft sensors and “hard sensors” as well as physical models to take the information to a higher level of utilization.

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