# DYNAMIC SIMULATION STUDIES FOR ENHANCED BOARD MACHINE CONTROL

**Jari Lappalainen[3], Jouni Savolainen[1], Tommi Myller[2], Kaj Juslin[1]**

*[1] VTT Technical Research Centre of Finland, P.O.Box 1301, Fin-02044 VTT, Finland*
*[2] Stora Enso Oyj, Fin-55800 Imatra, Finland*
*[3] Nalco Finland Oy, Fin-02150 Espoo, Finland*

Abstract: A dynamic simulation model of a 3-layer board machine was developed. The simulation model consists of stock preparation and proportioning, short circulations, wire and press sections, and drying section including the steam and condensate systems. Physical, first principles models were used whenever possible. The control system and automatic grade change program were modelled as well. The simulator was extensively validated against measurements. Two simulation cases concerning grade changes are discussed: re-tuning of the automatic grade change program, and studying the potential of a new dryer. *Copyright © 2005 IFAC*

Keywords: modelling, dynamic models, simulation, control applications, paper industry

## 1. INTRODUCTION

For a board machine that produces tens of different grades, grade changes (GC) have a large impact on the machine production efficiency. Dynamic simulation helps to understand the process dynamics, and the role of automation and operators in GC’s.

Grade changes have been discussed in many simulation studies in the literature. In 1988, Miyanishi et al. demonstrated the effects of machine chest volume, first pass retention, and dry broke ratio in GC. They also showed the effect of increasing filler loading in the initial period of the GC in which filler type is changed.

Many simulation studies deal with the question of how to automate the operations of a grade change. The basic idea of an automatic grade change program (AGC) is simple: ramping of manipulated variables with preplanned targets and mutual coordination. However, it is challenging to guarantee smooth and fast transient simultaneously for all quality variables, covering the whole operation area. Ihalainen and Ritala (1996) presented an idea to numerically optimize the actions in GC's by using dynamic simulation. Murphy and Chen (2000) proposed a dynamic coordinator to reduce the basis weight and moisture content upsets during GC's. Thick stock flow was used as a coordinating actuator. Non-linear control curve pattern was used by Mori *et al.* (2000).

The traditional AGC methods switch the machine's quality controls off when performing grade changes. Approaches to do GC's under feedback control, using model predictive control, have also been presented (Välisuo, *et al.*, 1996; Kuusisto, *et al.,2001*). The accurate prediction of moisture dynamics is prompted as a key challenge. The moisture model must handle the complicated dynamics due to the changing machine speed, paper basis weight and ash content, but still be easily commissioned and maintained.

Development of new process concepts is a fundamentally different approach to speed up GC's. In such studies, dynamic simulation has been successfully used as a tool in integrating the process and control designs. Kokko *et al.* (2001) used GC simulations to demonstrate the agility and controllability of a new wet end concept.

In this paper, experiences of using dynamic simulation to study and improve GC's in a Finnish multi-grade, multi-ply board machine are presented. The model structure and the main calculation principles are described. Simulation results are shown and two use cases discussed.

First, the simulator was used in tuning the present AGC system. Secondly, the potential of a new drying method (designed primarily to increase drying capacity) in moisture control during GCs was studied.

## 2. MOTIVATION FOR MODELLING: DEEPER UNDERSTANDING OF GRADE CHANGES

The board machine in question produces liquid packaging and graphical board grades with basis weight 170-350 g/m$^2$, at a speed of 200-450 m/min. The machine has three fourdrinier wires, one of them equipped with a top wire unit. There are three press nips in the press section. Five two-tier dryer groups with conventional steam-heated cylinders are used to dry the base board to approximately 3 % moisture prior to a size press. The following two steam groups before the on-line coating were also included in the simulation model.

An average of one GC per day is performed on the machine. For many years, an automatic grade change program has assisted the operators at the mill. The control variables that are included in the AGC are:

- wire speed
- thick stock flows (in all 3 head boxes)
- slice openings (in all 3 head boxes)
- jet/wire ratios (in all 3 head boxes)
- steam pressures in steam groups 5 and 7

The AGC program calculates targets for the thick stock flows and the steam pressures. The lower pressure steam groups follow the pressures in the 5th and 7th group with predefined ratios. The AGC also suggests typical grade specific operating values for the wire speed, the slice openings and the jet/wire ratios. The operator may change them if necessary. After the GC has been initiated, the AGC coordinates the mutual delays and handles ramping of the variables. This coordination is pre-planned by giving a start delay, maximum stepping rate and a stop delay for each variable in the GC, see figure 1. There are separate parameters for ramping upwards and downwards. Additionally, there is a selection of whether to synchronize or not the ramping of a variable with the others.

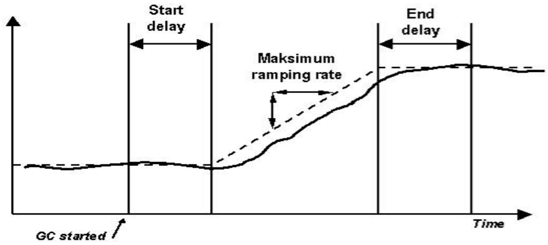

Fig. 1. Illustration of the main tuning parameters that each variable has in the AGC program.

Before a grade change the operators select which of the variables will be included in the AGC. Some operators let the automatics handle all the variables, but most often they prefer adjust the slice openings manually.

Before this simulation study the AGC parameters had not been altered after the commissioning of the program. The operators used the AGC actively. However, they felt the operation could still be improved by parameter tuning.

Disturbances in the board moisture content were one of the main concerns when planning to speed up GC's. Moisture bounces upwards or downwards when the machine speed starts to change, and again just after reaching the target speed. This occurs in most of the GC's, but the amplitude of the disturbance varies from case to case. Intuitively, with the tuning parameters available (figure 1) it should be possible to make the GC’s faster and simultaneously calm down the moisture fluctuation. However, it was very challenging to figure out the right actions needed using just a mental model. In a multi-ply machine like this the number of tuning parameters of the AGC is remarkable. The simulator was seen as a possibility to experiment with different ideas before anything was done on the real machine.

## 3. MODELLING

The board making process was modelled from the refining chests to the end of the base board drying. The aim of real-time or faster simulation set bounds for the modelling work. The model was built using the Apros Paper (formerly known as APMS) simulator which is based on first principles of physics whenever possible.

Most of the parameters needed, such as pipe diameters, tank volumes, nominal flows, pump heads for pumps, were derived from P&ID's. Pipe lengths were either calculated from piping drawings or estimated at the mill. Equipment elevations from a reference level were taken from layout drawings. Some of the parameters needed investigation of construction drawings (e.g. cylinder diameters and shell thickness) or were obtained from measurement data (e.g. pressure drops in the pressure screens). In the modelling, general engineering knowledge was needed too, because some specific information of an old piece of equipment is too laborious to find (say pressure drops and trim types of valves).

### *3.1 Mass Preparation and Short Circulation.*

Refining, mass proportioning and short circulation loops form a large thermohydraulic pressure/flow network which was modelled by connecting model objects for pipes, pumps, valves, screens, cleaners, tanks, etc., together. Temperature, level and composition in the refining chests set boundary conditions for the model. Three fibre components, filler and water are carried along in the system. This, of course, is a simplification to the real life flow situation. This simplification restricts the ability to simulate, for example, the chemical state of the system. On the other hand this kind of simulation was not required in the study and furthermore adding more components to the flows can easily be done with the simulator.

The modelling of the consistency dynamics was based on combination of ideal mixing and plug flow elements, created automatically by the simulator during model configuration. Fractionating in screens and centrifugal cleaners was defined with constant ratio for each of the stock components. Refining effects on dewatering and paper quality were not included in the modelling scope.

Head box was the last part of the pressure/flow network before the sheet model starts. The cross and thickness direction of the web was considered homogeneous in the model. Again, this is a simplification, which can again be justified with the scope of the study. This simplification, which saves a considerable amount of storage space and calculation speed, cuts out the possibility to enhance cross direction control developments. On the other hand it should be noted that this was not in the interest of the mill. In the machine direction the sheet was divided into user defined number of elements moving with the machine speed. The sheet properties calculated were: moisture content, temperature, basis weight, sheet composition and thickness.

### *3.2 Wire Section.*

Each head box initiates its own sheet model which carries the information concerning the layer to the connection point of the three layers. In the connection, the properties of the three layers are averaged and a new web model is initiated. Constant retention values are used for the furnish components in the wire sections. The simulator does allow variable retention coefficients but this feature was not used. In fact it might even be detrimental to have a bad retention model replacing the constant coefficient model. Comparison of the simulated and measured values of the head boxes' consistencies justified this approximation.

Drainage in wire section is a very important and yet a very challenging part of papermaking to model. In this case, sampling from the web in the end of the wire section turned to be too difficult, and the dewatering was modelled in a simple way. Constant splitting coefficients were used for dewatering from the separate layers. In the last part of the wire section, after averaging the layers, the dry solids content of the outgoing web was kept at a fixed value. The amount of the removed white water changed accordingly. In some grade changes this simplification worked very well since the operators control the dry line position with slice lip opening thus keeping the dry solids content in a certain range. When the slice lip is smoothly opened or closed to its new target value, the dry line does not necessarily move at all (Berndtson *et al.*, 1999). On the other hand, in stepwise changes typical for manual operation, changes in dry line and outgoing moisture content do take place.

### *3.3 Wet Press Section.*

In the wet press section, the water removal was calculated using the decreasing permeability model (McDonald and Amini, 2000):

$$\frac{z}{z_0} = \left(1 + \frac{4Anz_0^n I}{vW^2}\right)^{-1/n} \tag{1}$$

where

| | |
|---|---|
| $z$ | outgoing moisture ratio [kg $H_20$/kg dry paper] |
| $z_0$ | incoming moisture ratio [kg $H_20$/kg d.p.] |
| $I$ | press impulse = press load/speed [(kN/m)/(m/s)] |
| $n$ | compressibility factor |
| $A$ | specific permeability [g/m] |
| $W$ | basis weight [kg/m$^2$] |
| $v$ | viscosity of water [m$^2$/s] |

The factor 4 is used only for double felted nips. No rewetting needs to be considered due to the heavy basis weights. McDonald and Amini (2000) recommended determining the model parameters, compressibility factor and the specific permeability, by pressing hand sheets in a laboratory press. In this case, the model parameters were based on the published experiences of using the decreasing permeability model and on 21 measurement points from the machine. The measurements gave information on the dry content in different production situations after the press section. But, as already mentioned, the dry content of the incoming sheet could not be measured and thus straightforward parameter fitting was not possible. Still, the decreasing permeability model, with the selected parameters, seemed to give reasonable approximation of the machine's press section.

*3.3 Drying Section.*

The drying section was modelled cylinder by cylinder, including the steam and condensate systems. Steam headers and pipes from the power plant form a boundary condition of the steam and condensate system model. The condensate return flow to the power plant forms the other model boundary. The piping network of the steam and condensate system was modelled using the homogeneous two-phase flow model of the simulation platform. Figure 2 presents a view of the 2nd steam group.

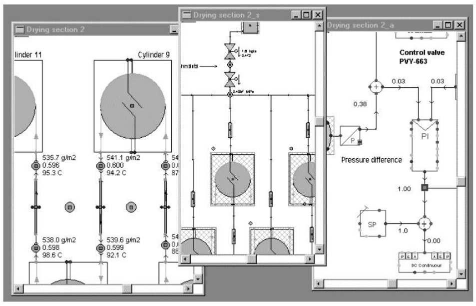

Fig. 2. Graphical specification of the model for each steam group is divided into three pictures: the sheet (left), the steam and condensate system (middle), and the related control loops (right).

Graphical specification of the model for each steam group was divided into three pictures: the sheet (left), the steam and condensate system (middle), and the related control loops (right).

In cylinder drying the steam condenses inside a cylinder and releases its latent heat. The condensate layer inside the cylinder is the first one to resist the heat on its way to the paper. In the model, the condensate heat transfer coefficients were derived from the measurements made on the drying section. The one-dimensional heat conduction model was used in the calculation of the heat flow through the cylinder wall.

The heat transfer coefficient between cylinder outer surface and paper was defined as a linear function of the paper moisture. The state of the paper sheet in each position in the machine direction, was described by average temperature, moisture and composition. In industrial paper drying, however, there exist gradients in the paper thickness direction in moisture and temperature. This was taken into account in the calculation by different means. For example, when paper is warming up in contact with cylinder, a portion of the web thickness is resisting the heat transfer. The dryer the paper is, the bigger the resistance of this portion gets.

The following approximation of the Stefan equation was used to calculate evaporation from paper to air (Heikkilä, 1993):

$$\frac{\dot{m}_{ev}}{A} = \alpha \cdot C \cdot \ln\left(\frac{p_{tot} - p_{va}}{p_{tot} - p_{vp}}\right) \qquad (2)$$

where

| | |
|---|---|
| $\dot{m}_{ev}$ | evaporating water [kg/s] |
| $A$ | paper area [m$^2$] |
| $\alpha$ | paper -to-air heat transfer coefficient [W/m$^2$°C] |
| $p_{tot}$ | air total pressure [Pa] |
| $p_{vp}$ | vapour partial pressure on paper surface [Pa] |
| $p_{va}$ | vapour partial pressure in surrounding air [Pa] |
| $C$ | constant $7.03 \cdot 10^4$ [kgH$_2$O°C/W/s] |

Vapour partial pressure for free water was calculated using Antoine's equation and the partial pressure in air was solved using user given air temperature, pressure and humidity in the dryer pockets. The state of the pockets was assumed to be constant during the GC's. The paper-to-air heat transfer coefficient depends on the machine speed, felting and whether the evaporation takes place during a cylinder contact or in a free draw. Below the critical moisture content, the evaporation front has moved into the paper. The reduction in partial pressure was approximated by using sorption isotherms. In addition, the resistance for vapour to move from the middle parts of the sheet to the paper surface was approximated by a reduction factor, originally presented for modelling of evaporation through a pigment coating (Heikkilä, 1993).

*3.3 Control System.*

The relevant parts of control system, 74 loops, were modelled in parallel with the process modelling. In addition, the functionality of the AGC program was modelled to enable what-if studies with new tuning parameter settings.

## 4. MODEL VALIDATION

One of the interesting questions when testing this kind of paper machine simulator was the accuracy of the dynamics in the short circulation. Grade changes produce good data for model development and validation, because of the big transients in such many variables. At the target machine, the DCS automatically collects data from every GC. No machine bump tests were made, and the samples from the sheet after the wet press was the only extra measurement effort done because of the modelling and validation.

Besides of the process data collected with the DCS, the mill had plenty of studies concerning various parts of the machine and many of those were useful in the model validation. Measurements from the experiments with radioactive tracers opened up a rare opportunity to compare the process dynamics related to delays and mixing in the approach system. Figure 3 presents results of one such experiment. The upper picture shows the measured data (Indmeas 1997). The tracer was fed into the thick stock lines just after the machine chests, and then measured at the head boxes. The lower picture presents the corresponding simulation. The delay calculation in pipes was based on plug flow combined with a small percentage of mixing. The wire pits were modelled with two ideal mixers in series.

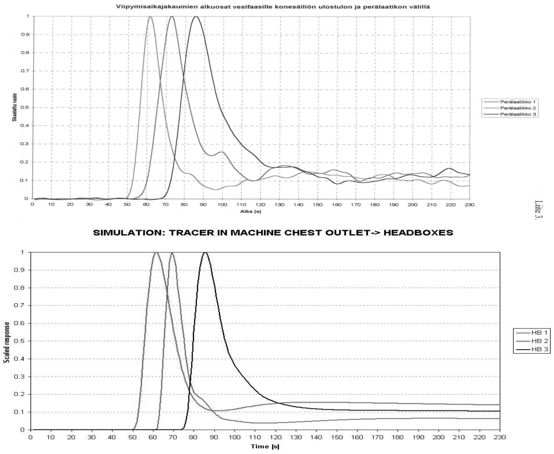

Fig. 3. Measured and simulated tracer concentration (scaled) in the three head boxes of the board machine.

In the tuning and validation of the drying section model, results of drying section performance studies made at the mill from time to time were used. In these studies, temperature measurements of paper, cylinder surface and dryer pockets (moisture as well) were taken by hand. An example of measured and simulated drying section profiles are presented in figure 4. The following simulated values are presented: steam temperatures inside cylinders, temperatures at cylinders' outer surface, web temperatures, and web moisture content in different positions. Because of the non-discretized thickness direction, there are no simulated sheet top and bottom temperatures. Instead, simulated temperatures in the beginning and end of each free draw are shown.

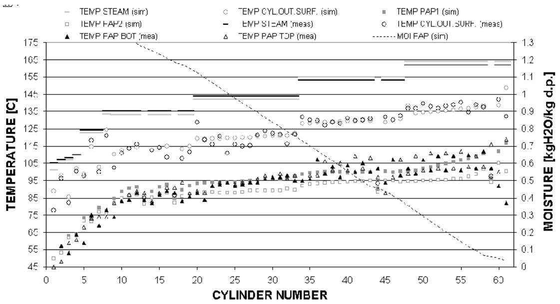

Fig. 4. Measured and simulated profiles at the drying section.

At the beginning of the comparison of the simulated and measured GC data, there were problems to get the AGC model to perform GC's identically to the actual AGC program at the machine. Differences appeared occasionally between simulations and the mill data, e.g. in the ramp of the machine speed. It was found out that some operators were using the AGC program in a slightly different way than expected and as was done in the simulations. By using the simulated GC's as reference undesirable actions were sieved out when aiming at best result with the AGC. For example:

- Some operators made the AGC to calculate the new target values in good time before the GC. Early calculated targets may not be proper any more when the GC actually starts. The best practice is to use the mode of automatic target updating. Then the final calculation is done just before the GC is initiated.
- When variables, e.g. slice openings, were left out from the automatic GC, they were sometimes blocked off by setting their lower level control loops in manual mode. As a consequence, these variables were still involved in the AGC's calculation procedure. With a coincidence of dummy target values, this led to too long ramping times for the active variables.

These faults were identified, and the operators were advised to the best practices in using the AGC program.

### *4.1 Simulation Example.*

The biggest challenge in simulating the GC transients was with the moisture dynamics, for more details see Lappalainen *et al.* (2001). Overall, the simulator showed very good agreement with the measurements.

Figure 5 presents a simulation example, where an actual GC is repeated with the simulator. The case is not a school example of a GC, but excellent for simulator testing. Measured values are drawn with black, and grey curves show the corresponding simulation. Time scale is presented in seconds, the total time being 55 minutes. Machine speed was ramped from 445 to 330 m/min. Thick stock flows of the top and bottom layers are practically equal and much smaller than the flow for the middle layer. The slice lip openings were controlled manually. A big increase in the main steam pressure was needed in this case. The time instants when the slice lip of the middle layer is opened, and the speed is changed can be clearly seen in the picture of the jet/wire-ratios (figure 6).

In this GC, the moisture content of the board was excessively high after the ramping phase (figure 7, around 900 s). Thus, manual operations were needed to get the moisture to its set point. Firstly, the steam pressure was raised to the maximum. Secondly, the machine speed was lowered three times. Clearly, this GC would have been more successful with better target prediction. No attention was paid to that part of the AGC in this study. Different prediction methods have been proposed in literature, see e.g. Murphy and Chan (2000), Mori *et al.* (2000), Viitamäki (2000).

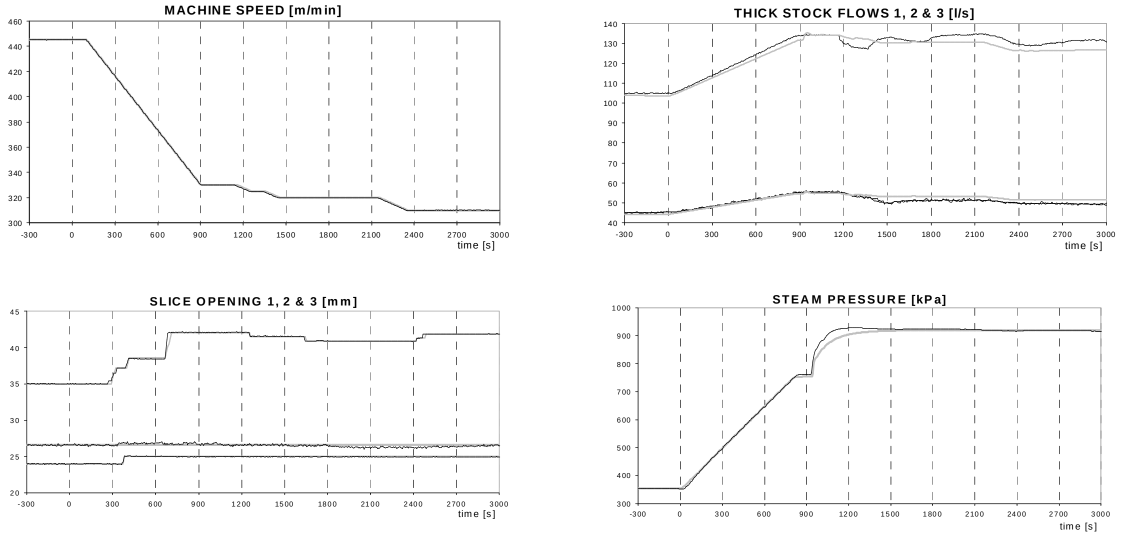

Fig. 5. Measured (black) and simulated (grey) variables in a GC: machine speed, thick stock flows of three layers, slice openings, steam pressure in the main steam group.

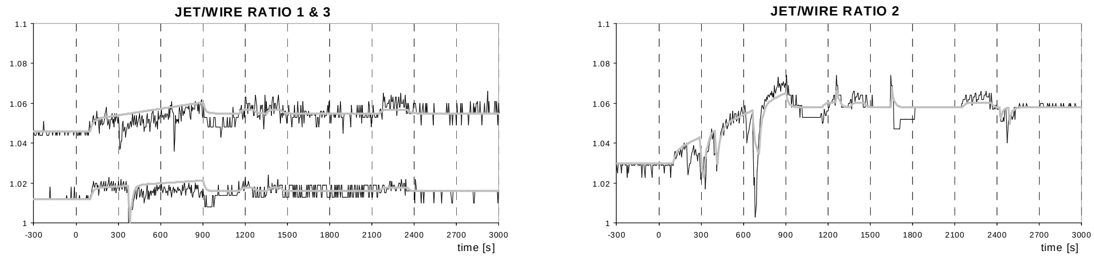

Fig. 6. Measured (black) and simulated (grey) variables in a GC: jet/wire-ratios of the top and bottom layers (left) and the middle layer (right).

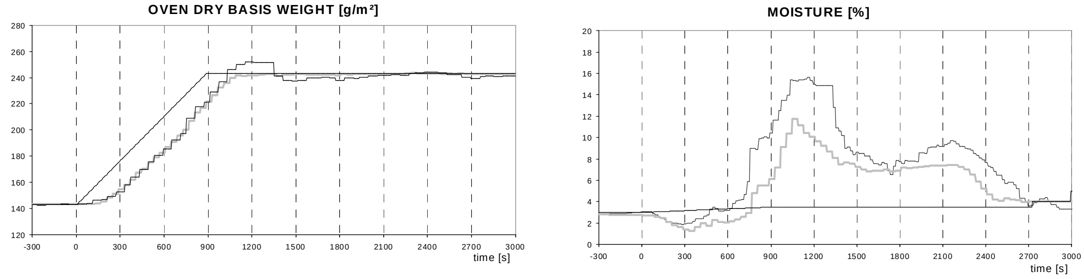

Fig. 7. Measured (black) and simulated (grey) variables in a GC: oven dry basis weight and moisture content. The corresponding set values are shown too

## 5. WHAT-IF STUDIES

### *5.1 AGC tuning.*

When the simulator could consistently repeat GC's made in the real machine, the what-if experiments with the tuning parameters were started. In the experiments, the data from the real GC's was always used as a reference.

The simulations were started by increasing the ramping rates of those variables, which most often limited the total ramping time. One by one higher rates were tried out and the effects on the performance analyzed. For example, the ramping rate of the machine speed was more than doubled. It was easy to shorten the time needed to change the basis weight. All machine circumstances and restrictions must be, however, considered. The amplitude of the moisture fluctuations slightly increased, but they also settled down faster. The moisture behaviour can be affected by altering the mutual timing of the ramps. Figure 8 illustrates how different parameter values affect on the moisture. The black curve shows the moisture in the reference GC. The corresponding simulation with the original values is marked with A. The curve B presents simulation where an optimal target value (found by simulation trials) for the main steam group was used. The curve C corresponds to a simulation with the optimal steam pressure target, and modified AGC tuning parameters. The example shows that there are two important requirements for a successful GC: proper target values, and correct synchronization of the control actions. The faster the variable ramps are, the more critical becomes the mutual timing. For both of the requirements, additional challenge comes from the large variety of different grades at the board machine in question.

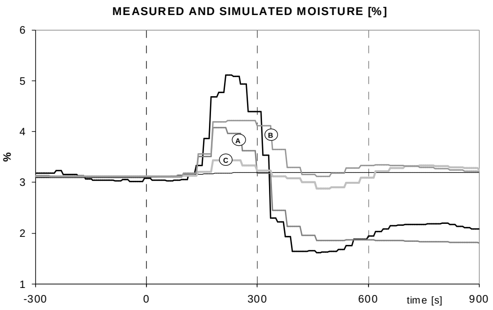

Fig. 8. Measured (black) and simulated (grey) moisture in a GC. Simulation experiments: repetition of the original GC (A), the original AGC tuning and an optimal steam pressure target (B), and re-tuned AGC and an optimal steam pressure target (C).

After experimenting the tuning with the simulator, a new set of tuning parameter values were implemented to the actual AGC program. Grade change performance before and after the changes was followed, and clear improvement in the GC times was registered. Notable was that there was no change in the simulator accuracy when the new GC's (with the re-tuned AGC) were simulated. This ensured the credibility of the simulator.

### *5.2 New fast dryer – capacity increase and better control.*

Increase of the machine drying capacity has been pondered upon at the mill. Recently, the use of an air impingement dryer, was studied more carefully. Impingement drying gives evaporating rates many times higher than conventional cylinder drying (Juppi and Kaihovirta, 2001). In addition, impingement drying provides several times faster control response to moisture than pressure controlled steam cylinders. More details about control of an air impingement dryer unit, and corresponding drying section concept, can be found in Kokko *et al.* (2002).

Planning of the new drying unit brought up a question of whether to utilize it in the moisture control during grade changes. The existing model of the target machine, as well as model of the impingement dryer unit (Tuuri *et al.*, 2001), made it straightforward to study the topic. The board machine model was extended with the dryer unit including the air system, the burner, the heat capacity of the iron etc., and all the needed low level controls. The main results of the control study were reported by Ansaharju (2002).

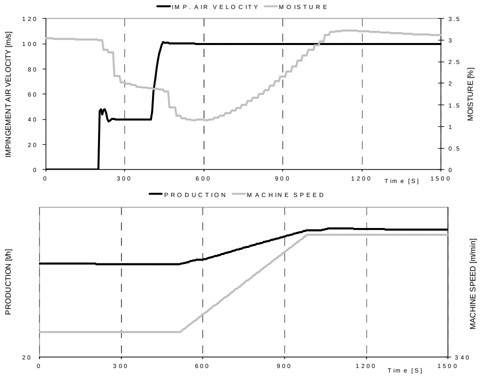

Fig. 9. Simulation experiment to study production capacity increase with the new dryer.

The increase in the capacity the new dryer could produce was one of the interests in the air impingement study. Besides static calculations with multiple methods, the dynamic model was used for the task. Figure 9 presents one such simulation experiment. A drying cylinder was replaced by an air impingement dryer unit (readily hot, control at 50%) at time 200s. Next, the control variable used, air flow velocity was increased to its maximum (at time 400s). Moisture content decreased, and the machine speed could be increased accordingly. The end point of the simulation experiment, where the capacity increase was calculated, was when the original moisture level is reached.

## 6. CONCLUSIONS

A Finnish 3-layer board production process was modelled from the pulp chests to the end of the base board drying. The developed model was rather large and complex. Especially the drying section of the board machine was modelled in great detail. The model was validated against measurements, especially using mill data from tens of grade changes. Modelling and validation phase helped to understand the interactions of process and automation in the grade changes. Additionally, some weaknesses were found in operational practices concerning the use of the AGC program.

For a multi-ply board machine, it is a demanding task to figure out how the AGC parameters should be changed to speed up grade changes and simultaneously keep the moisture under good control. The simulator helped to cut the problem into pieces, offered a way to visualize the problem and compare the solution candidates. Corresponding tuning parameters were implemented to the real AGC with good results.

The developed model offers a platform for troubleshooting, training and evaluation of suggested changes in the process. The drying section of the model was extended with an air impingement dryer unit, which, besides offering a high drying capacity in a small space, can be used for moisture control. With the simulator, different possibilities to utilize the new dryer's speed in moisture control during grade changes were tested.

A detailed, dynamic simulation model is an excellent tool in studying and improving operation and control of a complex system such as the 3-layer board machine in complicated transients such as grade changes.

## REFERENCES

Ansaharju, J. (2002). *Increasing drying capacity on a board machine*. Master's thesis. Helsinki University of Technology, Department of Forest Industry, Espoo.

Berndtson, J., A.J. Niemi, A.J. and S. Karine (1999). Experiences with automatic measurements and control of the dry line on wire. Proceedings of the XXVII EUCEPA Conference, Grenoble, pp. 131-136.

Heikkilä, P. (1993). *A study on the drying process of coated paper webs*. Ph.D. Thesis. Åbo Akademi, Turku.

Ihalainen, R. and R. Ritala (1996). Optimal grade changes. Proceedings of Control Systems '96, Halifax, pp. 213-216.

IndMeas Oy (1997). Internal measurement report for Stora Enso Oyj.

Juppi, K. and J. Kaihovirta (2001). Impingement drying of printing papers at elevated temperatures. *Tappi Journal*, **84** (7), 11.

Kokko, T., P. Lautala and T. Huhtelin (2002). Advanced control strategy for impingement drying. Proceedings of the 13th International Drying Symposium, Beijing, vol. C, pp. 1734-1746.

Kokko, T., M. Hietaniemi, J. Ahola, T. Huhtelin and P. Lautala (2001). Development of paper machine wet end using simulation. Proceedings of the 3rd EcoPaperTech, Helsinki, pp. 135-147.

Kuusisto, R., M. Kosonen, J. Shakespeare and T. Huhtelin (2001). Multivariable control of paper machine grade changes. Proceedings of 87th annual meeting of PAPTAC, Montreal, pp. C141-144.

Lappalainen, J., T. Myller, O. Vehviläinen, S. Tuuri, and K. Juslin (2001). Enhancing grade changes with dynamic simulation. Proceeding of Tappi Engineering Conference 2001, San Antonio, 11 p.

McDonald, D. and J. Amini (2000). Predicting the press dewatering of heavyweight grades. *TAPPI Journal*, **83** (2), 79-82.

Miyanishi, T., K. Iida and T. Iwatsu (1988). Dynamic simulation for efficient paper machine grade change. *TAPPI Journal*, **71** (1), 49-56.

Mori, Y., H. Shimizu, and K. Takao (2000). Development of a new automatic grade change control system for paper machine. Proceedings of Control Systems 2000, Victoria, British Columbia, pp. 231-234.

Murphy, T.F. and S.C. Chen (2000). Fast grade change for paper-making processes. Proceedings of Control Systems 2000, Victoria, British Columbia, pp. 189-192.

Tuuri, S., P. Heikkilä and K. Hamström (2001). Dynamic model of drying section including air impingement unit. Proceedings of the 3rd EcoPaperTech Conference, Helsinki, 11p.

Viitamäki, P. (2000). Hybrid modeling of moisture in paper machine grade changes. Proceedings of Control Systems 2000, Victoria, British Columbia, pp. 239-242.

Välisuo, H., A. Niemenmaa, J. Lappalainen, I. Laukkanen and K. Juslin (1996). Dynamic simulation of paper and board mills: a case study of an advanced grade change method. Proceedings of TAPPI Engineering Conference, Chicago, pp. 491-498.