Eucalyptus Chip Compaction Disturbance Analysis in a Vapor Phase Continuous Digester

Flávio M. Correia : Production Coordinator, CENIBRA, Brazil, flavio.correia@cenibra.com.br
Jorge L. Colodette : Full Professor, UFV, Brazil, colodett@ufv.br
Adair J. Regazzi : Full Professor,UFV, Brazil, aregazzi@ufv.br
José L. Gomide : Full Professor,UFV, Brazil, jlgomide@ufv.br

ABSTRACT

Kraft continuous digester production capacity has been increasing over the years, with large production in single line units. It has been increased by increasing the height in 1960's and enlarging the diameter after 1970's due to chip level control problems. This sets new challenges for flow controlling in the digester while maintaining uniform quality. Kappa number, which measures the pulp residual amounts of lignin and hexenuronic acids, has been the main digester control parameter. This parameter is influenced by many variables such as wood chip quality, temperature, alkali charge, and chips residence time. The latter is strongly influenced by the chip compaction phenomenon, which in turn affects the kappa number, the production rate and the digester chip level. One of the most difficult operational problems for the digester control is to stabilize the vertical movement of chip bed. The abnormal hydraulic column movement directly determines the residence time for the chips, reflecting the difficulties of controlling the chips and liquor level. Kraft pulping has been widely investigated, and the optimal cooking conditions concerning reaction chemistry and kinetics have been modeled by different authors. However, such models are applicable only to digesters under equilibrium conditions. A major issue on continuous digester operation is the appropriate control of chip level, which is strongly affected by the very large equipment dimension, the highly demanding process controls, the measurements uncertainties, the raw material quality variations, the high production rates and the long residence times. When chip compaction bed control is lost, affecting chip level, the reaction time also becomes out of control, causing problems of production, quality and product uniformity. There are different chip compaction disturbances causes in continuous digesters, and often it is difficult to identify and act on them immediately, considering the many variables involved and the synergy among them (even in highly automated systems). The interactions between these factors and the kappa number are complex, particularly during non stationary process conditions. The aim of this study was improving digester operational equilibrium, by clustering different key cooking process information that affect *Eucalyptus* chip compaction disturbance in a vapor phase continuous digester, evaluating the interaction between them and determining their effects on chip bed retention disturbances. The results achieved allowed for a better understanding of chip bed packing and turned possible the optimization of digester liquor and chip flows. Through modifications and advances on the main manipulated inputs, digester hanging and flow channeling were minimized with consequent improved fiber quality and production efficiency.

Keywords: Eucalyptus, Kraft cooking, Continuous Digester, Chip Bed Compaction, Hanging, Flow Channeling.

Introduction

The pulp production rates in continuous cooking processes have increased continuously. The modern plants are built with large capacity in single line, which requires higher and wider digesters over time. There are many disturbances in continuous digester control; one of the major is the abnormal chip compaction bed. This problem is aggravated in the new high capacity digesters, because of the complex phenomena involved in delignification reactions, and the long time delays in the measurements of critical variables. The complex thermal chemical phenomena associated to wood chips non uniformity make it difficult to maintain digester regularity.

After entering the top of the digester, the wood chips form a chip column that moves vertically down continuously. Chips generally retain their original physical dimensions throughout the cooking process and do not become fibers until after depressurization or "blowing" at the end of the digester. It is important to have optimal packing and flow conditions inside the digester, because too high packing and liquor flow channeling leads to non-uniform cooking, production losses and impaired fiber quality. Usually in the industry, the residence time of chips is calculated based on production rate, digester geometry and a given constant factor compaction profile provided by suppliers for steady state process, but in adverse conditions, is not calculated by any means [1]. The term "*chip compaction*" is used to express the intensity that chips are compressed inside of the digester, in relation to their feed volume. Packing is a common term to describe the conditions inside the digester. High chip bed packing occurs when the chip bed pressure is high and porosity is low [2]. Chip compaction, liquor and chip level control and their inter-relationship with the residence time are relatively little explored concerning their impact on pulp quality [3]. Few references deal with industrial data, among them Ahvenlampi and Kortela [4], Ahvenlampi *et al* [5], Allison [6], Michelsen [7], and Puranen [8].

Models that explain the phenomena of softwood chip compaction in continuous digester were studied by Harkoonen [9] who developed a model from momentum, mass and energy balances to describe the motion of the chip plug and the bulk liquor. The resulting model is a set of two-dimensional partial differential equations which are solved at steady-state to find velocity (wood chip and liquor), chip pressure, compaction and temperature profiles along the digester. Ahvenlampi and Uusitalo [10] studied the influence of plugging screen extraction and variations in the chip and liquor level. This is a typical control problem in continuous digesters, especially on those of vapor phase processes.

All continuous digesters generate a lot of information for operators. They have many measurements to monitor and control at the same time. The highly non-linear nature of the process and the long residence times hinder actions for correcting problems.

Clustering was the method used in this work aimed to optimize the continuous digester operation, using the approach to minimize chip compaction disturbances by grouping in a single number, a set of relevant operational process variables, namely: chip density, chip and liquor level (partial and full), cooking temperature, liquor extraction flow, screen pressure differential, pulp blow temperature and flow, discharge scraper current. Such variables were collected and stored through the DCS, applied to a fuzzy logic test in excel applicative, resulting in a chip compaction disturbance index. By knowing the trend of this index, digester operators can take fast decisions to minimize the impacts of retention time changes on pulp quality and production rate.

Continuous Kraft pulp digesters, are complex reactors, where heat and mass transfer, diffusion and friction occurring simultaneously with chemical reactions. It is important to know how different components are flowing in the reactor and how long take to flow trough the vessel. The chip bed is formed by association of chips and liquor inside the vessel, and does not have a uniform profile along the digester. The compaction and the downward movement of the chips changes as the chips transport through the digester. This is mostly due to the density difference between chips and liquid, and delignification reactions. Different forces affect the chip bed compaction, some in the same directions of chip movement, and others against. There are different factors affecting chip compactions, namely: pre-steaming, acting forces, liquor flow, chip flow, delignification reactions and liquor/chip level.

Chips are treated with steam or flash steam, in order to removes entrained air from chips by filling empty spaces with steam. Accumulation of air in the process can lead to pump cavitations, non uniformity in liquor penetration, and in extreme cases, the chips may present a lower density than cooking liquor, not achieving sufficient density to maintain the downward chip bed movement.

The acting forces in a force balance are gravity, buoyancy, friction between the digester wall and the chip column, and flow friction between the chip column and the liquor [11]. Gravitational force pushes the chip bed downwards. Buoyancy provides uplift for the chip bed. If the chip bed is stationary, the packing degree increases towards the bottom of the bed. Surface forces, pressure and friction, are those that act on the surface of the liquid and solid phases through it, considering the pressure and friction forces. The chip bed pressure is the force acting on the chip column divided by the digester cross sectional area of the chip column. When the chip bed moves downwards, the digester wall and downward chip flow subject the chip bed to a frictional force. The friction term is dependent on the directions and relative values of the flows of the chips and liquor inside the digester. These forces are dependent of the fluid viscosity and solid surface characteristics of the vessel wall [12].

The liquor flow either pushes the chip bed downwards or provides uplift for the bed. In a non-moving chip bed, the packing degree is highest in the bottom of the digester. But when the chips and liquor start to move and the cooking degree is taken into account, the packing in the chip bed is usually densest where two opposite liquor flows meet. Furthermore, the liquor flow inside the digester is not uniform. Near the digester walls the porosity of the chip bed is higher compared to the average bed packing. The liquor flow near the wall is faster than in the middle of the bed. Through the models of Jansson [13], was observed that the resistance of the liquor flow profile in the digester is a result of the degree of compaction and the amount of dissolved lignin from wood chips. He found that the free liquor flow, decreases along the digester. This reduction in the rate of flow is due to compression of the chips in the digester which decreases the free spaces in the column of chips and, consequently, increases the flow resistance. Higher packing degree affects liquor flow inside the digester. Lee and Bennington [14], in his studies on the flow of liquor into the chip column in continuous digester, reported that the continuous digesters operating above design capacity need to operate with a larger volume of chemical reagents by area equipment hindering the flow of movement. The liquid density is the main component that defines its general properties. It determines the buoyancy of the chips and thus the pressure in the chip column. In turbulent flow, the flow resistance is directly proportional to the density of the liquid.

The chip flow through the digester, determines the retention time exposed on each section of the vessel. The chip vertical velocity profile varies as the chips goes through the digester. This variation is caused by the diameter varying, liquor circulation and white liquor added interference, the delignification reactions, liquor level and the weight of the column. At the top of the digester, the chip moves faster downwards than liquor. The velocity difference decreases on the way down to the extraction point. The flow directions for chip and liquor are opposite in the wash zone, and the relative speed difference is highest there.

As the delignification process, the lignin content in the chips is decreased, making the chips softer. In this way, the chip column takes less space, because fibers fill the open volume around chips reducing the porosity and therefore, increasing the compaction. Based in laboratory data, the chip compaction in the digester was modeled by Härkönen [15] using the chip pressure and Kappa number.

In vapor phase digesters, the chip and liquor level difference is used to heat up the chips in the top part of the vessel, from impregnation temperature to cooking temperature. The level difference affects the initial bed packing by forcing downwards the chip column (lower the liquor level, lower the buoyancy force).

Material and Methods

Eucalyptus urograndis industrial chips (470 and 500 kg/m³ density) were used throughout the study. The wood chips that fed digester 1 derived from logs debarked in an industrial drum and those that fed digester 2 derived from logs debarked in the forestry with harvester equipment. The chips average dimensions were 18-25 mm length, 8-12 mm width, 2-8 thickness.

The experiments were run on two different industrial digesters. Digester 1 is a vapor phase Kraft continuous digester installed in 1977 with Kamyr technology, which was converted into the so-called KobudoMari cooking technology in 2000. It is 49.4 m high with a 6.1 m base diameter and delivers 500,000 ADMT/y of pulp at a kappa number 15-17. It features 227 different instruments directly linked to the equipment. Digester 2 is a vapor phase Kraft continuous digester installed in 1995 with technology ITC Kvaerner, which was converted into Lo Solids Andritz technology in 2006. It is 54.6 m high with a 7.6 m base diameter and delivers 700,000 ADMT/y of pulp at kappa number 15-17. It features 264 different instruments directly linked to the equipment.

The process data were collected over four months, with a fifteen minutes frequency, and stored in a PIMS - Process Information Management System, available to operators through the DCS - Digital Control System. The data from production with high pressure feeder running under 20 rpm were not considered and eliminated as outliers. A total of 11,174 and 11,308 observations were collected in digester 1 and 2, respectively.

The raw data and statistical variables were combined using fuzzy logic, thus generating a key factor for predicting faulty situations related to abnormal chip compaction disturbances. This factor is the so-called chip compaction disturbance index. High values indicate an unstable equilibrium, suggesting the operator to anticipate corrective actions. The following variables were used to calculate the index: temperature discharge, extraction liquor flow, blow line flow, chip level, partial and total liquor level, blow pressure drop, screen pressure drop, chip density drop, amperage discharge blow and circulations temperature. Scores of 0-2 were assigned to each one of these variables within the limits shown in Table 1.

Table 1: Variables used to calculate chip compaction disturbance index and their assigned scores and limits for both digester 1 and 2.

	Variable	**Limits**		
	score→	**0**	**1**	**2**
DD(*)	chip density drop (kg/m^3)	*< 5*	*5 -10*	*> 10*
NA	chip level (%)	*< 90*	*90 – 94*	*> 94*
NL	total liquor level (%)	*> 84*	*83 – 84*	*< 83*
NP	*parcial* liquor level *(%)*	*> 55*	*50 – 51*	*< 50*
VE	extraction liquor flow (m^3/RPM)	*> 9,8*	*9,8 - 9,0*	*< 9,0*
PEX	screen pressure drop $(mm\ H_2O)$	*< 0,18*	*0,18 - 0,20*	*> 0,20*
PD	*blow pressure drop* $(mm\ H_2O)$	*< -0,5*	*-0,5 - 0,0*	*> 0,0*
TD	*blow temperature (ºC)*	*< 82*	*82 – 86*	*> 86*
VD	*blow flow(* m^3/RPM*)*	*< 7,8*	*7,8 - 8,3*	*> 8,3*
AR	amperage discharge screw *(Amp)*	*< 115*	*115 -120*	*> 120*
TC	*circulation temperature (ºC)*	*< 166*	*166 – 168*	*> 168*
Y	***Compaction Disturbance Index (Y Index)***			

(*) – For digester 2, scored with 0.0 / 0.5 / 1.0 for the same indicated limits.

The final equation is a dynamic model, and gives the operator the main information to check cooking process. The total index is the sum of the values above indicated. Despite the importance of the kappa number, as it is a discrete variable and requires a long processing time to obtain, it was not used at the applicative.

Results and Discussion

Chip Compaction Disturbances

The compaction increases as it approaches the digester base, and is also be higher for a low production rate compared to a high production rate. The chip compaction problems can occur as *over-compact* or *under-compact*, and both of them are undesirable.

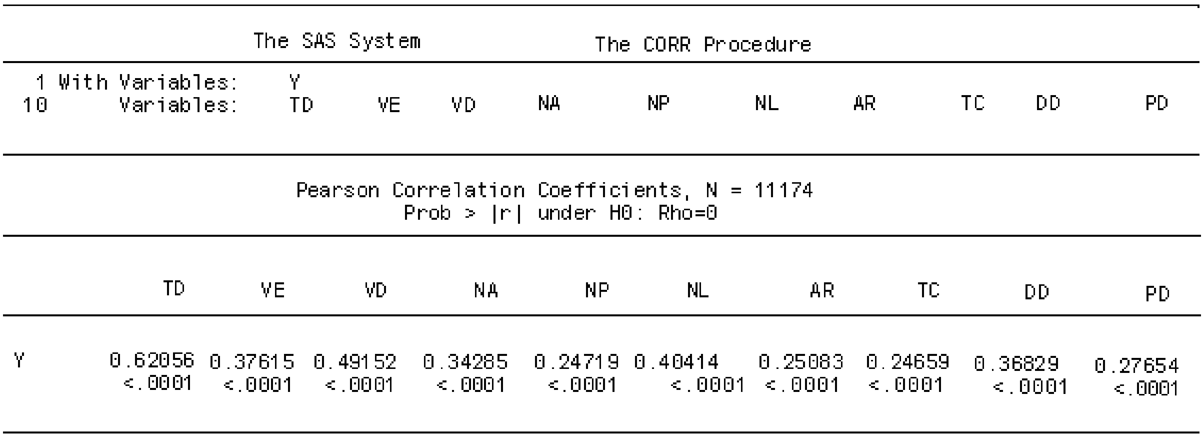
Chip compaction disturbances are characterized by irregularity in the hydraulic movement of the column and liquor channeling. Excessive compression at the digester base decreases the liquor permeability. In certain situations, a peak compression between the convergence zones (down flow and up flow) may occur causing a "column lifting". In other situations, some pulp plugging at screen area may block the natural chip flow in the vessel. If the column binds intensively at screens, it is necessary to reduce the chip feed flow, and increasing the pulp discharge (among other changes) at the same time.

Chip compaction disturbances characteristics are associated with abrupt changes in total and partial liquor levels, high chip level, high top digester pressure, high pressure drop indication at circulations and extraction screens, low blow screw amperage (caused by low consistency), peaks in blow temperature (resulting from liquor channeling) and others. The following are some actions used by mill personnel and recommended by some authors to reduce hanging digester problems : Minimize wood chip variations concerning to species, density, moisture, size; ensure good chip pre-impregnation with enough temperature and retention time [15]; increase digester top pressure in favor to increase the downward vertical flow ; reduce or eliminate up flow liquor circulations [16]; eliminate liquor extraction flow from high pressure drop screens , allowing chips flow to make a cleanup on the digester walls; increasing the difference from liquor and chips level [2]; minimize hi heat washing flow and finally avoid increasing the discharge flow above the production ratio to reduce under compacted zones impacts in digester equilibrium. Contribution of countercurrent liquor flow to the chip compaction disturbance is relevant. In first indications of instability, the up flow liquor should be reduced as soon as possible. The controlling of the cooking process is challenging due to the long digester residence time and much information to operators observes and control at the same time. Therefore grouping measurements into one is profitable.

Digester 1 Data

The Y index results were analyzed statistically by using SAS software, to identify the contribution of each variable to the compaction disturbance index (Y index) and their interactions. The sum of all contributions to the compaction disturbance index was 16,663 and the average value was 1.49. The confidence interval obtained for the population mean was 1.46 ≤ μ ≤ 1.52, with 95% confidence. The variable PEX (screen pressure drop) presented zero contribution in the composition of the Y index, because of instrumental problems at the period analyzed. Thus it was excluded from evaluation. Table 2 shows the correlation between variable and the Y index. The variable TD showed the highest correlation (r = 0.62).

Table 2: Correlation between Digester 1 variables and Compaction Disturbance Index



```
                    The SAS System                The CORR Procedure

  1 With Variables:    Y
 10      Variables:    TD      VE      VD      NA       NP       NL      AR       TC     DD       PD

                          Pearson Correlation Coefficients, N = 11174
                                   Prob > |r| under H0: Rho=0

              TD      VE       VD       NA       NP       NL        AR       TC       DD        PD

 Y        0.62056 0.37615 0.49152  0.34285  0.24719 0.40414   0.25083  0.24659  0.36829   0.27654
           <.0001  <.0001  <.0001   <.0001   <.0001   <.0001  <.0001   <.0001    <.0001    <.0001
```

By using the stepwise procedure, which was set up at a 10% probability, it was determined that the setting was perfect including all variables (R2 = 100%). With the adjusted equation for the index given by the sum of the contribution of all variables included:

$$\hat{Y} = TD + VE + VD + NA + NP + NL + AR + TC + DD + PD$$

Using the stepwise procedure, it was determined that the first six variables entering the model were TD, NL, VD, DD, TC and NA, explained the large majority of the Y index with a total R^2 = 91.56. The equation set for the first six variables aforementioned is:

:

$$\hat{Y} = 0{,}01125 + 1{,}02845^{*}.TD + 1{,}12405^{*}.VD + 1{,}12678^{*}.NA + 1{,}10346^{*}.NL + 1{,}13105^{*}.TC + 1{,}01439^{*}.DD$$

$$R^2 = 9.56\ \%$$

*(*)* - Significant at 1% probability by the t Student test. The above variables are identified in Table 1.

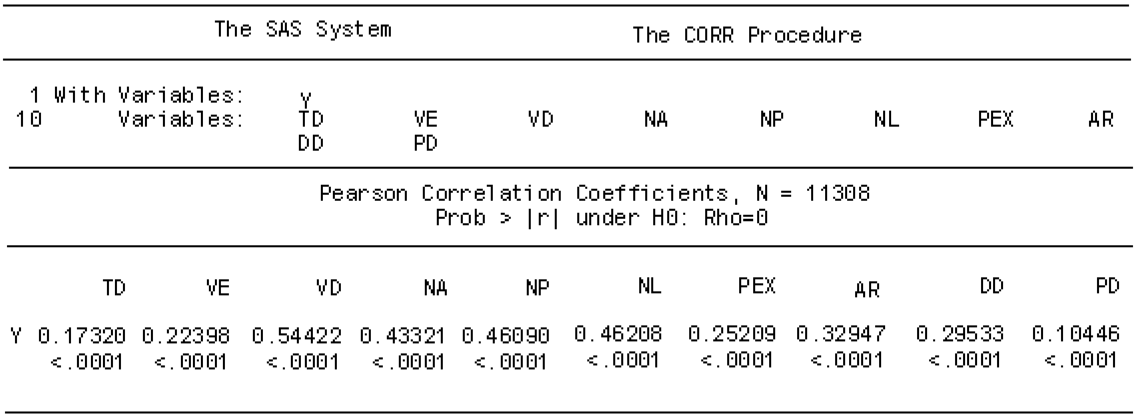
Digester 2 Data

The Y index results were analyzed statistically by using SAS software, to identify the contribution of each variable to the compaction disturbance index (Y index) and their interactions.

The sum of all contributions to the compaction disturbance index was 34,333.5 and the average value was 3.04. The confidence interval obtained for the population mean was 3.01 ≤ μ ≤ 3.06, with 95% confidence. The variable VD (*blow flow*) presented zero contribution in the composition of the Y index, because of instrumental problems at the period analyzed. Thus it was excluded from evaluation.

Table 3 shows the correlation between variable and the Y index. The variable VD showed the highest correlation (r = 0.54).

Table 3: Correlation between Digester 2 variables and Compaction Disturbance Index



```
                The SAS System                    The CORR Procedure

  1 With Variables:    y
 10      Variables:    TD       VE       VD       NA       NP       NL       PEX      AR
                       DD       PD

                      Pearson Correlation Coefficients, N = 11308
                               Prob > |r| under H0: Rho=0

        TD       VE       VD       NA       NP       NL       PEX      AR       DD       PD

 Y 0.17320 0.22398 0.54422 0.43321 0.46090  0.46208  0.25209 0.32947  0.29533  0.10446
    <.0001  <.0001   <.0001  <.0001  <.0001  <.0001   <.0001  <.0001   <.0001   <.0001
```

By using the stepwise procedure, which was set up at a 10% probability, it was determined that the setting was perfect including all variables (R2 = 100%). With the adjusted equation for the index given by the sum of the contribution of all variables included.

Using the stepwise procedure, it was determined that the first six variables entering the model were VD, AR, NP, TD, NA e DD, explained the large majority of the Y index with a total R^2 = 96.20. The equation set for the first six variables aforementioned is:

$$\hat{Y} = 0,06210 + 0,94297^{*}.TD + 1,03460^{*}.VD + 1,01530^{*}.NA + 1,53307^{*}.NP + 1,05236^{*}.AR + 1,04439^{*}.DD$$

$$R^2 = 96.20\ \%$$

*(*)* - Significant at 1% probability by the t Student test. The above variables are identified in Table 1.

Production Losses

The Y Index values determined previously were available online to digester operators, in order to help in the decision making process to minimize production losses. After the implementation of the Y disturbance index, there was a significant reduction of production losses due to digester chip compaction disturbances. In a period of 12 months ‘without Y index usage’ there were losses of about 4,000 adt for each digester. During the same period “with Y index usage” productions losses reduced to 450 adt.

Comparison between Digesters Data

The number of valid observations was very similar for both equipment (11,174 and 11,308 for the digesters 1 and 2 respectively). The average Y index of digester 1 was approximately half that of digester 2 (1.49 and 3.04 respectively). This is an indication that the digester 1 has a more stable operation when compared to digester 2, considering the upward liquor flows present in the digester 2 and absent in digester 1. Liquor up flow difficult the chip bed down movement as discussed above.

Four of the six most important variables are present in both digesters 1 and 2 (pulp flow discharge, pulp discharge temperature, chip density drop, and chip level). Similar references are found in the work of Puranen [8], which selected five variables for his mathematical model. He considered Kappa number, pulp consistency, pulp flow discharge, chip and liquor level, and the extraction pressure drop as most relevant ones. On the other hand, Puolakka [16] considered only three process variables: the difference between the liquor and chip level, the extraction temperature and extraction pressure drop.

Conclusions

The applicability of fuzzy clustering approach for the controllability of the chip compactions disturbance in vapor phase continuous digester was considered.

A good chip pre-steaming (time and temperature) in order to achieving sufficient density to maintain the downward chip bed movement is highly recommended to maintain chip bed continuous equilibrium, and avoid chip compaction disturbances.

Clustering cooking process variables is a good way to allow swift operators actions in digester control.

References

1. Rantanen, R.*;* Modeling and control of cooking degree in conventional and modified continuous pulping processes. *Ph D. Thesis*, University of Oulo, Norway, 2006.
2. Laakso, S.; Modeling of chip bed packing in a continuous Kraft cooking digester. *Dr. Sc. Thesis*, Helsinki University of Technology, Finland, 2008.
3. Wisnewski, P.; Doyle, F.; Kayihan, F.; Fundamental continuous-pulp digester model for simulation and control. Alche Journal, 43 (12), 1997, p 3175-3192.
4. Ahvenlampi, T.; Kortela U.; Clustering Algorithms in Process Monitoring and Control Application to Continuous Digesters. Informatica 29 (1), 2005, p 99-107.
5. Ahvenlampi T.; Rantanen, R. And Tervaskanto, M. Fault Tolerant Control Application For Continuous Kraft Pulping. In: 17th IFAC The International Federation of Automatic Control, *Proceedings*, 2006.
6. Allison, B. J.; Roberts, C.; Generalized predictive control of chip level in dual-vessel continuous digesters. Tappi Pulping Conference, Proceedings. 1995, p 115-123.
7. Michelsen, F.A.; A dynamic mechanistic model and mode-based analysis of continuous Kamyr digester. *Dr. Ing. Thesis*, 1995, University of Trondheim, Norway.
8. Puranen, T.; Jatkuvatoimisen sellukeittimen häiriöntunnistus sumealla logiikalla. Metso Automation Seminar. Helsinki, Finland. *Proceedings*, 1999, p 406-411
9. Harkonen, E.J.; A mathematical model for two-phase flow in continuous digester. *Tappi J.*, 70 (12), 1987, p 122-126.
10. Ahvenlampi T.; Uusitalo M. Diagnosis Of Extraction Screen Plugging In Continuous Cooking Application. In: 17th IFAC, the International Federation of Automatic Control, *Proceedings*, 2006.
11. Saltin, J A predictive dynamic model for continuous digesters. In: Tappi Pulping Conference. Boston, EUA, 1992, *Proceedings* p. 261–268.
12. Miyanishi, T.; Shimada, H. ; Improvement of pulp strength and yield by computer Simulation of lo-solids Kraft cooking. *Tappi Journal*, v 84, n 6 , 2001.
13. Jansson, J.; Digester modelling for diagnostics and control. Ph.D. Thesis, Mälardalen University, Västerås, Sweden, 2009.
14. Lee, Q. F.; Fluid flow through packed columns of cooked wood chips. *M.Sc. Thesis*, University of British Columbia, 2002
15. Malkov, S.; Leavitt, A.; Stromberg, B.; Improved understanding of chip steaming and impregnation. Engineering, Pulping, and PCE&I Conference, 2004
16. Puolakka, H_M.; Tervaskanto, M.; Ahvenlampi, T; Observation and visualization of the chip compaction disturbances in digester. In: Tappi Engineering, Pulping, Environmental Conference, *Proceedings*, 2005.