STATUS REPORTS

to the

PAPERMAKING

PROJECT ADVISORY COMMITTEE

VOLUME I

March 18 - 19, 1996
February 13, 1996

TO: MEMBERS OF THE PAPERMAKING AND THE PROCESS SIMULATION AND CONTROL PROJECT ADVISORY COMMITTEE

Attached for your review are the Status Reports for the projects to be discussed at the Papermaking and the Process Simulation and Control Project Advisory Committee meeting. The program review is scheduled for Monday, March 18, 1996, at 1:00 to 5:00 p.m. The Papermaking PAC and the Process Simulation and Control PAC committee meetings will meet separately during the morning of March 19, 1996, from 8:00 a.m. to 12:00 p.m.

We look forward to seeing you at this time.

Sincerely,

David I. Orloff, Ph.D.
Professor of Engineering & Director
Engineering and Paper Materials Division

DIO/map

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* The dates in ( ) indicate the final year of the appointment.
PAPERMAKING/PROCESS SIMULATION AND CONTROL
PROJECT ADVISORY COMMITTEE MEETING

March 18-19, 1996
Seminar Room
Institute of Paper Science and Technology
Atlanta, Georgia

AGENDA

March 18, 1996

1:00 p.m. - 1:10 p.m. Opening Remarks and Anti Trust Statement
Opening Remarks and Anti Trust Statement
David White

1:10 p.m. - 1:20 p.m. Overview of IPST Papermaking Research
Overview of IPST Papermaking Research
David Orloff

1:20 p.m. - 2:00 p.m. Project E00101 Headbox & Table Flow
Project E00101 Headbox & Table Flow
Cyrus Aidun

2:00 p.m. - 2:40 p.m. Project F002 Fundamentals of Web Heating
Project F002 Fundamentals of Web Heating
Tim Patterson

2:40 p.m. - 3:20 p.m. Project F001 Advances in Impulse Drying Research
Project F001 Advances in Impulse Drying Research
David Orloff

3:20 p.m. - 3:35 p.m. Break
Break

3:35 p.m. - 4:15 p.m. Project F003 Fundamentals of Coating
Project F003 Fundamentals of Coating
Cyrus Aidun

4:15 p.m. - 4:55 p.m. Project F006 Air-Sheet Interactions
Project F006 Air-Sheet Interactions
Xiaodong Wang

4:55 p.m. - 5:45 p.m. Student Research
Student Research
Barry Crouse

March 19, 1996

8:00 a.m. - 12:00 p.m. Papermaking Committee Discussions
Papermaking Committee Discussions
David Orloff
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<td>On the Research Areas of Approach Pipe Systems</td>
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HEADBOX AND FORMING HYDRODYNAMICS

STATUS REPORT

FOR

PROJECT E00101

Cyrus K. Aidun

March 18 - 19, 1996

Institute of Paper Science and Technology
500 10th Street, N.W.
Atlanta, Georgia 30318
TECHNICAL PROGRAM REVIEW

Project Title: HEADBOX AND FORMING HYDRODYNAMICS
Project Code: EXPLOR
Project Number: E00101
Division: Engineering and Paper Materials
Project Staff: Cyrus Aidun, Adrian Ferrier
Project Budget: $215,000

OBJECTIVES:

The objectives of this project are to:

(1) investigate and optimize the paper and board forming processes in the wet end of existing machines,

(2) develop novel methods for analysis and control of paper forming, and

(3) develop more effective headbox design and paper forming procedures

TASKS FOR FY'95-96:

1. Fix the IPST paper machine.
2. Design a generic hydraulic headbox (G1) for the IPST pilot paper machine.
3. Construct a computational model of the generic headbox.
4. Install the G2 headbox in the CE Hydraulics Lab.
5. Fabricate and install the G1 headbox on the IPST paper machine.
6. Start high-speed flow visualization studies of the flow in the G1 headbox and the jet/wire interaction.
7. Examine mechanisms for increasing the CD strength properties in the forming section and reducing streaks (CD basis weight nonuniformities) on the existing forming tables, with flow modification in the:
a. G1 headbox using dye injection;
b. G2 headbox using Laser Doppler anemometer (at the CE Lab.); and
c. G1 headbox using computational analysis.

8. Install a Laser-Doppler anemometer on the IPST paper machine.
9. Measure the secondary flows in the headbox and the effect of various headbox modifications on the hydrodynamic characteristics at the slice and on the forming table.
10. Using a pilot machine, examine the effect of various modifications to the headbox on the physical properties of the sheet.
11. Analyze the effect of turbulent flow in the headbox and on the forming wire, on fiber and filler dispersion/flocculation/distribution, and paper formation.

TIME TABLE (starting Sept. 1, 1995)

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ACCOMPLISHMENTS:

- A generic headbox has been designed and constructed for installation on the IPST pilot machine (parts of the tube bank are being completed at the GTRI machine shop);

- High-speed imaging of several commercial paper machines with different grades have been completed - the images are being analyzed to shed light on the various forming mechanisms which cause CD nonuniformities; and

- Effectiveness of a mechanism to enhance formation characteristics has been computationally verified - experiments with a modified version of IPST's headbox will start in the near future. We are waiting for parts of the tube that are being made at GTRI machine shop.

FUTURE ISSUES:

- A combination of high-speed image analysis and computational methods is being used to better characterize the role of the headbox hydrodynamics and the forming section on CD nonuniformities in basis weight, fiber orientation, and physical properties;

- The effectiveness of new features which can be added to current operating headboxes are being explored; and

- The computational results and analysis need to be complemented with pilot trials and tests on commercial machines.
SCOPE OF THE PROJECT:

Based on the first Headbox & Paper Forming questionnaire, the top three issues of importance are:

i. CD nonuniformities (basis-weight, streaks, fiber orientation, moisture, filler and fines distribution, etc.)

ii. Enhance CD properties (stiffness), ring-crush, STFI, etc.

iii. Understand and improve formation (fiber dispersion in the headbox and on the forming wire, etc.)

The long-term issue of importance is:

i. Design an optimized headbox and forming section
RESULTS OF THE FIRST QUESTIONNAIRE ON HEADBOX AND FORMING HYDRODYNAMICS

<table>
<thead>
<tr>
<th>Areas of importance</th>
<th>Average rating for degree of importance</th>
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<td>(The averages are based on 32 responses from 21 member companies)</td>
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<td>Fiber orientation nonuniformity in CD</td>
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<td>Basis-weight and/or Caliper nonuniformity in CD</td>
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<td>Moisture variation in CD</td>
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<td>Improve average CD strength</td>
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<td>Improve formation</td>
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<td>Improve formation uniformity</td>
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<td>Effect of tube geometry and pattern on formation</td>
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<td>Optimum headbox geometry and design</td>
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Others (please list below)

- "Enhance CD strength, CD stiffness, ring crush, STFI, ..."  
  __1__
- "Headbox hydrodynamics and forming table interaction"  
  __1__
- "Tools for HB analysis, 2 sidedness, MD variation, surface smoothness"  
  __2__

Please outline the most important issue that should be the focus of this project:

- "CD nonuniformity, formation, CD strength,..."

---

1 A second questionnaire on the specific headbox issues has been prepared by Dr. Yung Woo and Dr. Jay Shands and will be distributed to the PAC members, shortly.
EFFECTS OF TURBULENT CHARACTERISTICS ON FORMATION:  
THE COMPUTATIONAL RESULTS FOR THE G1 HEADBOX

One of the objectives of this project is to investigate mechanisms to improve formation and the uniformity of fiber distribution. It is well established that the turbulence characteristics in the headbox have a major impact on fiber dispersion. Also, it is generally agreed that more uniform fiber dispersion in the headbox results in better formation. Obviously, the characteristics of the flow in the forming zone, once the fluid leaves the slice, plays an important role as well. There have been many studies of the effect of turbulence on fiber distribution and the breakup of fiber flocs. The general conclusions are that the floc size reduces with increases in the stress level. Both extensional stress and shear stress are believed to break up the flocs through surface erosion, fragmentation, or stretching. The experiments by Lee and Brodkey (AIChE J., 33, 2, 1987) with flocs in a turbulent Couette flow clearly demonstrate this behavior. They also provide a crude model for the approximation of the normalized floc size with the stress level. This model, in a slightly different form, is given by

\[
\Delta t = \frac{1}{3.7(\tau - 0.6)} \ln \left( \frac{S_0}{S} \right)
\]

where \( \Delta t \) is the time (in seconds) it takes for a floc's size to change from \( S_0 \) to \( S \). The shear stress (N/m²), \( \tau \), is uniform in the experimental flow field (note that in Lee and Brodkey's paper, the 'yield stress' is written incorrectly as 6, instead of 0.6). Since the stress in this flow is constant, one can rewrite this model in terms of the turbulent viscosity, \( \mu_t \), by replacing \( \tau \) with \( \mu_t u/h \), where \( u \) and \( h \) are the appropriate characteristic velocity and length scale to define the correct local mean strain. In the \( k-\varepsilon \) model of turbulent flow, where \( k \) is the turbulent kinetic energy and \( \varepsilon \) is the turbulent viscous dissipation, the turbulent viscosity is defined by \( \mu_t = \rho k^2/\varepsilon \). Therefore, one can see the qualitative effect of turbulent kinetic energy and dissipation on the
characteristic time for the reduction of floc size. Here, we generalize Eq. (1) and rewrite this model to estimate the time required for 90% reduction of the floc size,

\[ \Delta t = \frac{1}{10\alpha \left( \mu \left[ \nabla v + (\nabla v)^T \right] - \tau_o \right)} \]  

(2)

where \( \tau_o \) is a type of yield stress representing the minimum stress required to disrupt the flocs and \( \alpha \) is a constant. Both \( \tau_o \) and \( \alpha \) depend on the fiber and floc material characteristics and need to be determined experimentally. The bracket \( [ \left[ \right] \) in the denominator represents the magnitude of the strain tensor-multiplied by the turbulent viscosity. It gives a measure of the total stress the floc experiences in the turbulent field. Here, one can consider \( \Delta t \) to represent the time scale for complete erosion and fragmentation of each floc. This model is qualitative in nature and should be treated as such. In the experiments of Lee and Brodkey with softwood pulp, the constants \( \alpha \) and \( \tau_o \) are determined to be 3.7 and 0.6, respectively. The turbulent viscosity and the magnitude of the strain rate should be determined either from computational analysis of the headbox or experimental measurements.

We have completed the computational model of the G1 headbox that is being built for the IPST paper machine. Some preliminary results are presented for two different cases. The first case, which is identified as Case A, is the base case where the flow has not been disturbed or modified in any form. This case represents a typical headbox in commercial production. The second case, Case B, simulates a modified headbox where axial vortices are generated upstream of the converging zone. The purpose for the generation of these vortices is to increase the turbulent energy level and, consequently, to enhance fiber dispersion and uniformity. Based on the models presented in Eqs. 1 and 2, the time scale for the complete destruction of a floc of fiber and uniform distribution of the fibers scales as the inverse of the turbulent viscosity. The turbulent viscosity is proportional to the turbulent kinetic energy squared divided by the turbulent viscous
dissipation. In order to examine the effectiveness of the modifications, we study the turbulent flow characteristics at the slice of the headbox. The flow rate and other flow characteristics are the same between both cases; therefore, direct comparison is possible.

In Figs. 1 to 4, we show the variation of the turbulent eddy viscosity and the turbulent kinetic energy at the slice for cases A and B, respectively. Each plot has four curves which show the value of the quantity from top to bottom of the slice at four different CD locations along the periodic cell of the tube bank.

Considering the turbulent kinetic energy and viscosity for each case in the middle region of the slice, we see that these quantities for case B are approximately five times larger in magnitude than the base case. However, near the wall, the values are almost the same for both cases. Based on Eq. 2, the characteristic time for the dispersion of fibers in case B should be much smaller than the base case. This means more effective fiber distribution and better formation in Case B relative to Case A.

The other issue is the characteristic length scale of the eddies as compared to the floc size. The eddy characteristic size, $L_e$, for Cases A and B are plotted in Figs. 5 and 6, respectively. The scale changes roughly by a factor of two. The effect of the turbulent scale on floc fragmentation is not well understood. However, it is reasonable to assume the following line of reasoning. Large flocs start to disintegrate in a turbulent field generally due to surface erosion and fiber shedding. The important mechanism here is the interaction of eddies with the flocs. However, as the floc size reduces, fine scale turbulence is more effective in the final fragmentation process. Therefore, a turbulent scale should in general reduce in size with the floc size.

The conclusion from this part of the study is that addition of axial vorticity upstream of the converging zone results in significantly higher turbulent kinetic energy at the slice and, consequently, better fiber distribution, uniformity, and formation.
GOALS FOR THE NEXT PERIOD

The major goal for the next period is to complete the experimental setup with the new G1 headbox; to install an LDA system on the machine; and to make detailed measurements of the flow characteristics inside the headbox, at the forming jet, and on the wire. We also will continue to study mechanisms for improving formation and uniformity in paper and board.
Figure 1.
Turbulent Kinetic Energy Distribution at the Outlet

Case A

Position Z on the Outlet Plane

- Edge
- Quarter
- Middle
- Far Quarter
Figure 3.
Turbulent Eddy Viscosity Distribution at the Outlet

Case A

Position Z on the Outlet Plane

0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20

0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00
Figure 4.
Turbulent Eddy Viscosity Distribution at the Outlet

Case B

Position Z on the Outlet Plane
Figure 22

Film Flowrate vs Inlet Flowrate

- - $U_{web} = 20 \text{m/s}$
- - $U_{web} = 30 \text{m/s}$

Inlet Flowrate (l/s)/m

Film Flowrate (l/s)/m
Figure 6. Eddy Characteristic Size Distribution at the Outlet.

Case B

Position Z on the Outlet Plane

0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20

0.005 0.010 0.015 0.020 0.025 0.030 0.035 0.040 0.045 0.050

Edge Quarter Middle Far Quarter

Position Z on the Outlet Plane

0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20

0.005 0.010 0.015 0.020 0.025 0.030 0.035 0.040 0.045 0.050
FUNDAMENTALS OF WEB HEATING

STATUS REPORT

FOR

PROJECT F002

Timothy F. Patterson
David I. Orloff
Paul Phelan
Isaak Rudman

March 18 - 19, 1996

Institute of Paper Science and Technology
500 10th Street, N.W.
Atlanta, Georgia 30318
I. OBJECTIVE:

To develop a quantitative understanding of the processes occurring during web preheating and during pressing of heated webs. Such an understanding will make possible the optimum use of web preheating for both production increases and product quality increases.

II. SUMMARY:

A. Background

This project is an outgrowth of work done under project F001. In that work, a steam box comparator was constructed that could serve as a means for evaluating various strategies for web preheating. Preliminary experiments showed that a vacuum box placed under a steambox could substantially improve the penetration of heat into the web. The Papermaking PAC recommended that work on the fundamentals of web heating be undertaken as a separate project. This new project takes the place of a project on Fundamentals of Water Removal that became vacant with the death of Prof. Z. Cai in January of 1995.

The project currently has two main areas of focus:

1. Web Preheating
2. Hot Pressing
The first area consists of an investigation of the fundamental mechanisms governing steam heating of a moving paper web. The second consists of an investigation into water removal and sheet properties which result from pressing a preheated web. The reason for the dual approach is that while web preheating improves water removal it can have other effects. If web preheating is to be employed, it is necessary to know both how to preheat and what are the results of pressing a preheated web. These two areas of study are being pursued simultaneously.

B. Program Objectives

Web Preheating

GOAL: Comprehensive model of web preheating

**Input:** furnish, felt, speed, steambox type, desired temperature profile

**Output:** steam flow rate, steam temperature, steam jet velocity, vacuum box length, vacuum box cover type, actual temperature profile, expected cooling rate

**Uses:** Determine if steambox use is economical, where in the machine it should be placed, if vacuum is necessary, how vacuum should be applied.

**Key Personnel:** Timothy Patterson, David Orloff

Hot Pressing

GOAL: Predictive model of water removal and changes in sheet properties due to incremental increases in ingoing web temperature.

**Input:** furnish, web temperature, press pulse

**Output:** water removal, post pressing and final web properties: density, caliper, ring crush, mullen, tensile

**Uses:** Determine if preheating is desirable, determine extent of preheating required.

**Key Personnel:** Timothy Patterson, David Orloff, Paul Phelan, Isaak Rudman
C. Goals and Results: October 1995 - March 1996

At the Fall 1995 PAC meeting, a number of immediate research objectives were stated. The plan was to attempt to complete these objectives by March 1996. In an effort to produce a more coordinated research effort, the priority of these tasks was rearranged. Priority was given to identifying an appropriate mathematical model for the steaming problem. A mathematical model provides a quantitative means of evaluating the factors affecting the web preheating process. Placing a priority on developing a quantitative method also provides a framework from which to decide the most appropriate experimental approach.

Any model requires an experimental verification and, in some cases, experimental determination of specific variables. Two furnishes were chosen for the experimental portion of this project, both web preheating and hot pressing: a 100% OCC furnish and a 100% Virgin Kraft furnish. These represent extremes of what is used in linerboard production and were chosen to limit the size of the experimental matrix. Both web preheating and hot pressing involve flow (gas, vapor, or liquid) throughout the web. Thus, there should be some similarity in the parameters governing the two processes. Measurements made to characterize a furnish for one process may be equally applicable for the other process. Thus, the experimental plan incorporates the measurement of air permeability, water permeability, specific surface, and the use of the results to develop correlations for both processes.

The objectives presented at the Fall PAC are listed here in the order presented at the meeting. A brief statement of progress made up to this point is also given.

1. Determine if there is a correlation between specific surface and sheet heating.
   - Work initiated. Specific surface measurements completed for one furnish (OCC). The initial water permeability work showed a need for improvement in the permeability test method. The improvements were implemented and the OCC furnish tested at three solids levels. The work is
presented in this report. Specific surface determination of the second furnish (Virgin Kraft) is planned for March/April 1996. Steambox Comparator experiments with the OOC furnish are planned for Spring 1996. The permeability and specific surface measurements will also be used in the hot pressing study listed below.

2. Identify major factors influencing the effectiveness of vacuum in steam heating - Steambox Comparator Tests (MS Thesis)
   - Experiments 50% complete as of 5 February 1996, planned to be 100% complete by 28 February 1996. This report presents some of the early test results.

3. Investigate applicability of existing heat and mass transfer models to web heating.
   - A literature search was performed and a model selected. The model is presented in this report. Implementation of the model, for the internal sheet processes occurring during steaming, is scheduled to begin in February/March 1996.

4. Determine relative importance of boundary layer in steam heating - Steambox Comparator Tests.
   - Work postponed, see Section IV. D. Planned Work for updated schedule.

5. Use the MTS one-dimensional press to determine: If there is a correlation between specific surface, sheet temperature, and web dewatering. If there is a correlation between specific surface, sheet temperature and STFI.
   - Work initiated. As stated in 1., the water permeability and specific surface measurements for the OCC furnish are complete. Pressing of the OCC furnish at three ingoing solids levels and three ingoing web temperatures is scheduled for February/March 1996. An ENP pulse shape will be used for the pressing.
The work performed since the last PAC meeting is presented in this report. A work plan for the upcoming six months is also presented. The area of Web Steam Preheating is addressed in the Section IV. The area of Hot Pressing is addressed in Section V.

III. SURVEY

At the Fall PAC meeting, a survey was distributed to the PAC. A total of six responses were received. The survey questions and the level of interest in each area are summarized below:

I. What applications of steamboxes are of the greatest interest to you?

1. Heating for productivity - machine speed increase High
2. Heating for profile control Medium
3. Heating for quality enhancement Medium

II. For the particular applications you cited, what aspects of steam box operation warrant further research?

1. Interaction with sheet structure Medium
2. Interaction with felt Low
3. Location of steambox on paper machine High
4. Location of steambox relative to press High
5. Location of steambox relative to vacuum box High
6. Steam flow rate High
7. Steam temperature (superheat) Medium
8. Steambox design Medium
9. Vacuum box design Medium
10. Steambox alternatives (infrared, microwave, etc.) Low

The results show that the primary interest of the respondents is to increase productivity, which is the primary stated goal of this project. It is generally acknowledged that increasing
the web temperature results in increased water removal in the press, which in turn can result in energy savings or increased machine speed. These results can be enhanced by using an “optimum” steambox setup. There are individuals who are capable of specifying an effective steambox setup for a given press section, but this knowledge is based on years of experience and is not generally available. Currently, there is no quantitative method for deciding which steambox setup is optimum for a particular situation. Examples of implementation problems for which there are no quantitative answers include: what is the optimum steam jet velocity (direction and speed)?, steam flow rate?, and vacuum setup?

The survey indicated that there is also an interest in the areas of profile control and quality improvements. The area of quality improvement brings into consideration the pressing process. It is generally acknowledged that increasing the web temperature prior to pressing can result in web property changes such as increased densification, decreased roughness, and decreased oil absorbency. There are a number of empirical studies demonstrating this type of result. However, there are no quantitative means of determining the changes nor how those changes will vary with furnish. In addition, there is limited information on how the changes affect frequently used measures of quality such as STFI and ring crush.

Effective profile control in the press section is both a steaming issue and a controls issue. Profile control is not specifically part of this project. This project is directed at quantitatively determining the mechanisms controlling preheating. However, the quantitative methods developed by this project can be applied to any steaming problem. The methods can be mated with a control strategy, resulting in enhanced profile control. The steaming method will define factors such as jet velocity, flow rate, etc. The control strategy and desired profiling results will define zone width, control system operating frequency, actuator response times, etc.

Addressing the high and medium priority areas requires a quantitative method of evaluating the factors effecting web preheating and heated web pressing. Currently, no such methods exist. There are only empirical studies addressing specific pressing implementations and
the considerable qualitative knowledge of individuals with extensive experience in these areas.

The survey also showed that there is little interest in steambox alternatives. It was the general opinion that the low cost and easy access to steam make it the heating means of choice.

IV. WEB STEAM PREHEATING

A. Summary

Web Preheating is a complicated problem involving a number of parameters (See Figure 1). Before a quantitative method useful for mill applications can be developed the fundamental physical processes must be understood. Therefore, the problem is going to be approached in segments:

1. Processes occurring inside the sheet
2. Steam jet impingement on the sheet surface
3. Vacuum application
4. Conduction and convection processes after exiting the steambox.

The processes occurring inside the sheet will be addressed first as these are the essential elements of the problem. An initial model for this portion of the problem is presented in the following paragraphs. The other factors can initially be treated as boundary conditions. Once the model of the internal sheet processes is developed the problem of steam jet impingement will be considered. That part of the investigation will also include the issue of air entrainment and boundary layer effects. The results will be added to the model of the internal sheet processes. The next issue considered will be the application of vacuum to the steaming process. This portion of the investigation will include vacuum box placement, felt interactions, and the issue of vacuum level versus flow rate. The last
problem to be considered is the processes which occur after the sheet has exited the steambox. These processes are internal sheet conduction, conduction to the felt, and surface convection from the sheet and felt. Once it is understood what has occurred under the steambox, these processes are relatively simple to describe.

![Diagram](image)

Steam Energy = \( f(\text{temperature, pressure, mass flow rate, velocity, dwell time}) \)

Boundary layer = \( f(\text{speed, sheet surface, steam box geometry}) \)

Air = \( f(\text{speed steambox geometry}) \)

Sheet Permeability = \( f(\text{furnish, solids, temperature, basis weight}) \)

Felt Permeability = \( f(\text{construction, material, moisture, dirt}) \)

Vacuum = \( f(\text{slot width, slot spacing, dwell time, vacuum level, air volume flow rate}) \)

**Figure 1. Factors Affecting Web Heating**
B. Steaming Model

A literature search was conducted into published and unpublished literature from the paper industry and from related industries. Extensive theoretical treatment of porous media and modeling of liquid and/or gas flow through porous media were found. However, the majority of this work focused either on nonfibrous porous media and/or geological processes. There was little that is applicable to the problem of steaming paper. There was some experimental work that was either applicable to paper webs or directly investigated steam heating of paper webs. This work provides some insight into the trends that can be expected, but it does not provide any quantitative methods that can be used to determine an optimum setup for a particular application.

A number of individuals were contacted about unpublished work in the area of steam preheating. The general response was that the work had either already been published or that it was proprietary. One individual provided a file containing the results of several experimental studies. He indicated that he has a large volume of data available, but did not have any information on modeling of the steaming process. This experimental data may be valuable once a model is constructed.

The published literature from the textile industry did yield some work on modeling steaming of porous media. Research in the textile industry on the steam heating of fiber beds has shown that a reasonably accurate analytical model can be constructed using the principals of conservation of mass, conservation of momentum, and conservation of energy. A specific implementation is given by C. V. Le, N. G. Ly, and R. Postle in “Heat and Mass Transfer in the Condensing Flow of Steam Through an Absorbing Fibrous Medium” published in the International Journal of Heat and Mass Transfer (Vol. 38, NO 1. pp. 81-19 1995). This model was applied to a wool fiber bed which was thicker than the typical paper web, and the time scale was longer than the typical steambox dwell time. However, the model is important because it considers a fiber bed. Also, the model takes into account the existence of water in the bed prior to the beginning of the steaming process and the existence of a pressure difference across the bed during
the steaming process. Perhaps the most important aspect of the model is that it has been
shown to be accurate in predicting steaming performance. This has been shown through
verification with experiments.

The proposed model for studying web steam preheating is based on the Le, Ly, Postle
model. Adjustments for the differences in dimension and time scale can be easily made.
There is some work that needs to be done in determining material properties and tailoring
some of the assumptions made by the model to the specific case of paper web. The
assumptions made in the model are as follows:

1. The sheet is thermally insulated from the environment and is assumed to exchange heat
   and mass only with the penetrating steam. Given the short period of the steaming
   process, ~0.030 - 0.050 seconds for a web traveling at 2500 fpm under an 18-in long
   steambox, this is a reasonable assumption. It is not a valid assumption once the sheet
   exits the steambox.

2. The ideal gas law is assumed for the vapor (gas) phase. This assumption is accurate for
   superheated steam and will be used initially for the case of saturated or near saturated
   steam. While it is not as accurate for the saturated case, it does simplify the model.

3. The heat transfer by radiation and conduction between fibers is assumed to be
   negligible. This assumption is based on the short time period of the steaming process.
   There is not enough time for conduction to be a significant factor (See Appendix A).
   Radiation is not a factor because the temperatures are too low.

4. Low convective velocities are assumed. Thus, diffusion of moisture in the gas phase is
   assumed negligible.

5. In the textile implementation of the model, the liquid phase (condensate) is assumed
   immobile and in thermal equilibrium with the solid phase (fibers). Whether or not the
liquid phase is immobile in a paper web may be questioned. Experiments are currently in progress to evaluate this factor. At this time it is planned to incorporate liquid mobility into the model.

6. The flow inside the sheet is assumed to be Darcian, natural convection and gravitational effects are ignored. This assumption may be questioned, as the flow of steam in the sheet may or may not reach steady state. It can be proved or disproved by comparing the results of this model to experimental data. Three possibilities exist for steam flow inside the sheet:
   a. The steam flow penetrates part way into the sheet.
   b. The steam just reaches the opposite side of the sheet.
   c. The steam penetrates completely through the sheet and reaches a steady state velocity.

Order of magnitude calculations for the time to reach steady state and the minimum time for the flow to go through the sheet are presented in Appendix B. If it is found that steam regularly passes through the sheet, then assumption 1. will be modified.

1. Principal Equations

Conservation of Mass

The principal of conservation of mass can be applied to the solid, liquid and vapor (gas) phases. In this model, water in the “solid” phase is water which is bound to the fibers.

Solid Phase:

\[ \rho \frac{\partial \varepsilon_b}{\partial t} = m_b + m_v \] (1)
where
\[ \rho_f \] - density of fiber
\[ \varepsilon_b \] - volume fraction of bound water
\[ \cdot m_s \] - rate of mass transfer from liquid (free water) to solid (bound water) phase
\[ \cdot m_v \] - rate of mass transfer from vapor (gas) to solid (bound water) phase
\[ \tau \] - time coordinate

The typical moisture content of a sheet exposed to steam heating is 55-80% (20-45% solids), which is more than the equilibrium content for paper (i.e., the moisture content of a sheet in equilibrium with a “room temperature” environment). Therefore, vapor and liquid absorption into the fibers can be neglected, giving

\[
\frac{\partial \varepsilon_b}{\partial \tau} = \cdot m_s = \cdot m_v = 0
\] (2)

The water added by the steam is assumed to go only into the pores.

Liquid Phase:

In the general case, liquid water can be absorbed into the fibers, evaporate into the vapor phase or change position within the sheet. The textile implementation of the model assumes that the volume fraction of liquid water in the sheet is below that required for mobility. In that case the equation for conservation of mass in the liquid phase is given by,

\[
\frac{\partial}{\partial \tau} (\varepsilon_l \rho_l) = \cdot m_i + \cdot m_s
\] (3)
where

\( \varepsilon_l \) - volume fraction of liquid water
\( \rho_l \) - density of liquid water
\( \dot{m}_u \) - rate of mass transfer of liquid (free water) to solid (bound water) phase.
\( \dot{m}_{vl} \) - rate of mass transfer of liquid to vapor phase.

As described in the solid phase, \( \dot{m}_u = 0 \). Equation (3) becomes

\[
\frac{\partial}{\partial t} (\varepsilon_l \rho_l) = \dot{m}_{vl} \quad (4)
\]

If the liquid phase does move within the sheet, then the term

\[
\frac{\partial}{\partial z} (\rho_l \dot{u}_l)
\]

is added to the left hand side of the equation giving,

\[
\frac{\partial}{\partial t} (\varepsilon_l \rho_l) + \frac{\partial}{\partial z} (\rho_l \dot{u}_l) = \dot{m}_{vl} \quad (5)
\]

Vapor (Gas) Phase:

Mass conservation in the vapor phase must take into account the change in the total amount of vapor as well as local changes in the vapor flow rate. The resulting equation is

\[
\frac{\partial}{\partial t} (\varepsilon_v \rho_v) + \frac{\partial}{\partial z} (\rho_v \dot{u}_v) = -\dot{m}_o - \dot{m}_{vl} \quad (6)
\]

where

\( \varepsilon_v \) - volume fraction of vapor
\( \rho_v \) - density of vapor
\( z \) - coordinate direction through thickness of sheet
\( \dot{u}_v \) - vapor velocity
\( m_v \) - rate of mass transfer from vapor (gas) phase to solid (bound water) phase

\( m_d \) - rate of mass transfer from vapor (gas) phase to liquid phase

As stated previously \( m_s = 0 \), giving

\[
\frac{\partial}{\partial t} \left( \rho_v \right) + \frac{\partial}{\partial z} \left( \rho_v u_v \right) = -m_d
\]

(7)

Conservation of Energy

Solid and Liquid Phase:

In applying the conservation of energy, the solid and liquid phases are considered together. The general equation is

\[
(\varepsilon_i \rho_i c_{pi} + \varepsilon_l \rho_l c_{pl}) \frac{\partial T}{\partial t} = h a_s (T_v - T_s) + \Delta h_{vap} \left( \dot{m}_v + \dot{m}_d \right) + \Delta h_{eff} \left( \dot{m}_s + \dot{m}_d \right)
\]

(8)

where

- \( c_{pi} \) - heat capacity of fiber
- \( c_{pl} \) - heat capacity of liquid
- \( h \) - internal convective heat transfer coefficient
- \( a_s \) - specific surface of the solid/unit volume (equal to specific surface \( S \), m\(^2\)/kg times density, kg/m\(^3\))
- \( T_v \) - temperature of vapor
- \( T_s \) - temperature of fiber
- \( \Delta h_{vap} \) - heat of evaporation or condensation
- \( \Delta h_{eff} \) - differential heat of absorption

Since \( \dot{m}_s = \dot{m}_d = 0 \), Eq. (8) becomes
\[
(\varepsilon, \rho, c, \varepsilon, \rho, c) \frac{\partial T}{\partial t} = h_{a} (T_r - T_i) + \Delta h_{\text{sw}} m_i
\]  

9)

In this equation, when condensation occurs, the liquid water at the fiber surface is assumed to equilibrate instantaneously.

Conduction to the top surface of the sheet, due to steam condensing directly on the surface of the sheet, can be taken into account by modifying Eq. (9) as follows

\[
\left(\varepsilon, \rho, c, \varepsilon, \rho, c\right) \frac{\partial T}{\partial t} = \left(\varepsilon, k, + \varepsilon, k\right) \frac{\partial^2 T}{\partial Z^2} + h_{a} (T_r - T_i) + \Delta h_{\text{sw}} m_i
\]

10)

where

- \( k_i \) - thermal conductivity for fiber
- \( k_i \) - thermal conductivity for water

The conduction term also adds two boundary conditions to the problem.

Vapor (Gas) Phase:

The conservation of energy equation for the vapor phase is given by

\[
(\varepsilon, \rho, c, \varepsilon, \rho, c) \frac{\partial T_v}{\partial t} + (\rho, c, \rho, c) u_c \frac{\partial T_v}{\partial Z} = -h_{a} (T_r - T_i)
\]

11)

If air is assumed to be inside the sheet then (11) becomes

\[
(\varepsilon, \rho, c, \varepsilon, \rho, c) \frac{\partial T_v}{\partial t} + (\rho, c, \rho, c) u_c \frac{\partial T_v}{\partial Z} = -h_{a} (T_r - T_i)
\]

11')

where

- \( \varepsilon_{a} \) - volume fraction of air
- \( \rho_{a} \) - density of air
- \( c_{pa} \) - heat capacity of air

Air will be neglected in this analysis because, in comparison to steam, its contribution to the energy balance will be small and it will add to the complexity of the model. Air in the sheet will change the water permeability and the thermal conductivity. The significance of these changes will have to be evaluated.
Conservation of Momentum

Vapor (Gas) Phase:

In the textile implementation of this model, the only moving element is the vapor. The vapor flow is assumed to be Darcian, giving

$$\frac{\partial P_v}{\partial z} = -\frac{\mu_v u_v}{K}$$ (12)

where

- $P_v$ - pressure of the vapor
- $u_v$ - velocity of the vapor
- $\mu_v$ - viscosity of the vapor
- $K$ - Kozeny-Carmen Constant

$$K = \frac{\varepsilon_v^3}{5.5 \cdot \rho_v \cdot (1 - \varepsilon_v)}$$

Taking into account the change in the vapor flow rate, Eq. (12) becomes

$$\frac{\partial}{\partial t} (\rho_v, u_v) + \frac{\partial}{\partial z} (p_v) + \frac{\mu_v u_v}{K} = 0$$ (13)

Liquid Phase:

In this implementation the movement of liquid will be included. If there is movement of liquid within the sheet, an additional momentum equation is required. The equation takes the same form as that for the vapor momentum.

$$\frac{\partial}{\partial t} (\rho_l, u_l) + \frac{\partial}{\partial z} (p_l) + \frac{\mu_l u_l}{K} = 0$$ (14)
2. Model Formulation and Observations

The equations for mass, energy, and momentum conservation are restated below.

**Conservation of Mass**

Liquid
\[
\frac{\partial}{\partial t} (\varepsilon_i \rho_i) + \frac{\partial}{\partial z} (\rho_i u_i) = m_d
\]  
\(5\)

Vapor
\[
\frac{\partial}{\partial t} (\varepsilon_v \rho_v) + \frac{\partial}{\partial z} (\rho_v u_v) = -m_d
\]  
\(7\)

**Conservation of Energy**

Liquid and Solid
\[
(\varepsilon_i \rho_i c_p + \varepsilon_v \rho_v c_p) \frac{\partial T}{\partial t} = \left( \varepsilon_s k_s + \varepsilon_v k_v \right) \frac{\partial^2 T}{\partial z^2} + h_{a} (T_v - T_s) + \Delta h_{\text{vap}} m_d
\]  
\(10\)

Vapor
\[
(\varepsilon_v \rho_v c_p) \frac{\partial T_v}{\partial t} + (\rho_v c_p u_v) \frac{\partial T_v}{\partial z} = -h_{a} (T_v - T_s)
\]  
\(11\)

**Conservation of Momentum**

Vapor
\[
\frac{\partial}{\partial t} (\rho_v u_v) + \frac{\partial}{\partial z} (\rho_v u_v u_v) + \frac{\mu_v u_v}{K} = 0
\]  
\(13\)

Liquid
\[
\frac{\partial}{\partial t} (\rho_l u_l) + \frac{\partial}{\partial z} (\rho_l u_l u_l) + \frac{\mu_l u_l}{K} = 0
\]  
\(14\)

An additional equation is the equation for volume fraction
\[
\varepsilon_s + \varepsilon_l + \varepsilon_v = 1
\]  
\(15\)

These equations constitute the main element of the model for processes occurring within the sheet during steaming. In addition to these equations, there are several equations associated with the calculation of mass transfer rates. These are as follows:
Mass Transfer Due to Condensation

\[ m_d = h_m a_s (p_i - p_v) \]  
\[ Q = h a_i (T_v - T_s) \]

Related Heat Transfer Coefficient

\[ Q = h a_i (T_v - T_s) \]  
\[ h_m = \frac{h}{\rho g c_p \text{Le}^{2/3}} \]  
\[ \text{Le} = \frac{\alpha_s}{D_b \text{Le}} - \frac{\alpha_s}{\epsilon_g D_a} \]

where

\( Q \) - rate of heat transfer

\( a_s \) - specific surface of the solid/unit volume (equal to specific surface S, m²/kg times density, kg/m³)

\( \alpha_s \) - porous media thermal diffusivity

\( D_b \) - porous media diffusion coefficient for water vapor

\( D_a \) - air diffusion coefficient for water vapor

\( \text{Le} \) - Lewis Number

\( h_m \) - mass transfer coefficient

The model is formulated by considering the problem to be one dimensional in displacement. It may be solved using finite difference methods. Although it does not appear that the equations can be solved analytically, that possibility will be investigated.

In the textile implementation of the model, the temperature distribution through the sheet was considered to be an unknown. In that case, the model was solved using a backward finite difference scheme. This method starts with the following initial conditions

\[ \varepsilon_{d_x}^{i+0} = 0 \]  
\[ T_{d_x}^{i+0} = T_{d_x}^{f+0} = T_{L_x} \]  
\[ P_{d_x}^{i+0} = P_{v0} \]

and boundary conditions

\[ P_{v_x=0} = P_{v}^{in} \]  
\[ P_{v_x=L} = P_{v}^{out} \]  
\[ T_{v_x=0} = T_{v}^{in} \]
The thickness of the bed was separated into 250 grid points and the time step set to 1/600 of the total process time. Given the initial conditions and the boundary conditions, the condensation/evaporation rates and the heat and mass transfer rates at the steaming interface were calculated. The amount of energy transferred, as related to condensation, was then computed. The energy equations were used to calculate the temperature distribution. At the next grid point the change in volume fraction of vapor and liquid was calculated using the conservation of mass equations. The mass transfer rates were calculated. The permeability equations were calculated at each grid point, from those results the average flow velocity is calculated using the momentum equation.

This method can be used to solve the equations for the case of steam heating of a paper web. It assumes a reasonable knowledge of the material constants involved. An alternative method is to use the equations with experimentally obtained temperature data. This data would include temperature variations with distance through the sheet and with time. The data can be obtained using the Steambox Comparator. This approach would allow verification of the material constants and of the assumptions made for the momentum equation (i.e., the flow is Darcian). Verification and implementation of the model will probably involve both approaches.

Examination of the conservation equations shows the reason for two experimentally observed steambox characteristics:

1. As sheet temperature increases, heating efficiency decreases.
2. As steam flow rates rise, heating efficiency decreases.

Eq. (10) shows that for a given steam flow rate through the sheet the rate of temperature increase in the sheet decreases as the difference between the sheet temperature and the vapor temperature decreases.

Eq. (13) and Eq. (7) show that as the permeability of the sheet decreases, the amount of vapor that can flow through the sheet decreases. As the flow through the sheet is
decreased, the rate of temperature increase will decline. Higher steam flow rates will cause more condensation at the top of the sheet, which will in turn decrease the permeability of the sheet and the vapor flow rate. Experience with air permeability testing has shown that as the sheet water content increases the permeability decreases.

In applying these equations to the steam heating of a paper web, the primary unknowns are:

\[ \alpha_s \quad - \text{porous media thermal diffusivity} \]
\[ D_w \quad - \text{air diffusion coefficient for water vapor} \]
\[ h \quad - \text{internal convective heat transfer coefficient} \]
\[ a_s \quad - \text{specific surface of the solid/unit volume} \]
\[ K \quad - \text{Kozeny-Carmen Constant} \]

Since all of the listed quantities can be expected to vary with furnish, moisture content, and to some extent temperature, it is expected that a correlation can be developed with steaming conditions and resultant temperature profiles.

The specific surface, \( a_s \), can be calculated from experimental results. The technique is currently used in water permeability tests that are routinely performed at IPST. The Kozeny-Carmen Constant, \( K \), can also be readily calculated. The air diffusion coefficient for water vapor can be found in the literature. If the thermal diffusivity is known then the thermal conductance, \( k \) can be calculated.

Another unknown is the heat capacitance of the fibers. This quantity will vary with furnish to a far less extent and there are experimentally determined values in the literature.

The unknowns most difficult to determine are the convective heat transfer coefficient and the thermal diffusivity. Experimental techniques need to be developed to determine these for wet paper. Mark Strand made an initial attempt at determining the thermal diffusivity...
of wet paper in his master’s thesis (Design and Development of a Device for the Measurement of Moist Paper Web Thermal Conductivity, IPST 1995). This work was only partially successful.

C. Model-based Considerations and Experiments

1. Determination of Convection Coefficient, $h$

The determination of the heat transfer coefficient is a difficult problem. One possible means is suggested in the work of Degan, Vasseur, and Bilgen [27]. The method involves experimentally determining the temperature distribution for a dry sheet exposed to a flow of hot dry air. The experimental distribution is then compared to the theoretically calculated distribution. From this comparison, the Nusselt Number can be calculated and presented as a function of Reynolds Number and Prandtl Number. The convection heat transfer coefficient can then be calculated. An approach similar to this was attempted by Donna Cansler in her master’s thesis (Steambox Analysis: Development of a Convective Heat Transfer Coefficient, IPST 1995). There were a number of experimental problems, related to equipment limitations, encountered during this work. It was not possible to obtain reliable convection coefficient values. These approaches will be evaluated and a method selected in the next few months.

3. Determination of Thermal diffusivity, $\alpha_t$

As stated in the previous section, Mark Strand attempted to determine the thermal diffusivity of wet paper in his master’s thesis. The values of thermal diffusivity in the literature vary considerably. There is also general agreement that there is a variation with temperature and moisture. A method of finding the thermal diffusivity needs to be determined if the proposed model is to be exercised with a high degree of accuracy. Two methods are possible:
1. Steambox Comparator Tests

This would involve experimental determination of an “effective” thermal diffusivity. The proposed method is to seal the top surface of the sheet from steam and moisture penetration and then subject the sheet to a steam flow. The steam will condense on the surface of the sheet without penetrating into the pores. The resultant temperature changes in the sheet will be due entirely to conduction. The thermal diffusivity for these conditions can then be calculated. The values obtained would not be exact properties.

2. Rebuild The Conduction Device of Mark Strand

The device constructed by Mark Strand was only marginally successful. However, he provided valuable insight into the problem and made a number of suggestions for an improved device in his thesis. In this approach, the device would be redesigned and rebuilt. It could then be used to measure thermal diffusivity of wet paper at various moisture contents and temperatures. Implementation of this alternative would require greater effort, but would provide better data.

The relative expense and expected results of these two approaches will be evaluated over the next several months.

4. Master’s Thesis - John C. DeBraal

Objectives of Thesis

J.C. DeBraal’s master’s thesis has three primary objectives:

1. Determine whether or not vacuum box slot size is a significant variable.
2. Determine whether or not liquid movement occurs within the sheet.
3. Compare the relative validity of the Darcian flow assumption vs. a Navier Stokes formulation of flow.

At this time (5 February 1996), approximately 50% of the experiments are complete. The remainder of the experiments should be completed by the end of February. The experimental matrix has been arranged so that most of the runs provide data for all three objectives. The result of this arrangement is that despite completing 50% of the tests, there is only enough data to address one of the thesis objectives at this time. The only case which is near completion is the liquid movement case. This involves using two vacuum boxes:

1. One which lies directly under the steambox and is the same length as the steambox, approximately 11 inches.
2. One which lies directly under the steambox, but also extends past the rear edge of the steambox. This vacuum box is approximately 20 inches long.

In all the runs the sled speed is approximately 2000 fpm. Some of the initial data is given in Appendix C. This data is for six runs, three using the 11-in vacuum box cover and three runs using the 20-in vacuum box. In all six runs, the vacuum level was about 5 in Hg. The steam flow was 145 kg/hr and had a temperature of 105-108°C at the steambox exit. Pressure in the steam box was 14 psig.

There are eight graphs presented in Appendix C. The first four are for the 11-in cover, three give the actual thermocouple readings for the time the sample was under the steam box. The fourth gives, for each run, a weighted average temperature for the sheet with time. The weighted average is calculated as follows:

\[ T_{avg} = \frac{(TC1+TC2)/2 \times \text{Basis wgt. 1st layer} + (TC2+TC3)/2 \times \text{Basis wgt. 2nd layer}}{ } \]
In these tests the layers all had the same basis weight, 41 g/m. The second four graphs provided the same information for the 20-in vacuum box cover.

In examining the graphs several things should be noted:

1. 11-in box dwell time at 2000 fpm - 0.275 seconds.
2. 20-in box dwell time at 2000 fpm - 0.050 seconds.
3. The thermocouple TC1 rests on top of the sheet. It registers a temperature rise when the sample enters the steambox.
4. Each succeeding thermocouple is beneath an additional sample layer.
5. There was no TC6, TC7 is beneath the sample and on top of the felt.
6. Sudden steep temperature rises are characteristic of temperature increases due to condensation.
7. Gradual temperature rises are characteristic of temperature increases due to conduction.

An examination of the graphs shows that in the cases with the 11-in cover, the condensation temperature increases occur during the ~ 0.030 seconds the sample is above the vacuum box and beneath the steambox. In the 20-in vacuum box cover cases, the steep temperature rises occur over a time period of ~ 0.040-0.045 seconds. The weighted average temperature increases while the sample is under the steambox and then continues to increase when the sample is past the steambox, but still above the vacuum box. The weighted average temperature rise is, in some ways, a measure of energy input into the sheet. Thus, the data could indicate that energy continues to be added to the sheet after the sheet has passed the steambox. A possible explanation is that the vacuum is sufficient to drag steam past the rear edge of the steambox. Additional analysis will need to be
done to confirm that this is the case and also to determine if this data gives an indication of liquid movement within the sheet, as we suspect.

D. Planned Work

1. Overview

Listed below are the research objectives for the next 24 months. This plan is somewhat ambitious, given that the required personnel have other commitments outside of this project. A possible cause for delays in the schedule is the determination and implementation of a means of determining the convective heat transfer coefficient and the thermal diffusivity.
2. Schedule

<table>
<thead>
<tr>
<th>Task</th>
<th>Jan '96</th>
<th>March '96</th>
<th>June '96</th>
<th>Oct. '96</th>
<th>March '97</th>
<th>October '97</th>
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<tbody>
<tr>
<td>MTS Pressing of OCC Furnish</td>
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<tr>
<td>1. Test Plan w/ Pre and Post Pressing Tests</td>
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<td>2. Pre pressing tests</td>
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<td>3. Pressing</td>
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<td>4. Post pressing tests</td>
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<td>5. Data analysis/write up</td>
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<tr>
<td>Permeability Tests of Virgin Kraft Furnish</td>
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<tr>
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<td>2. Permeability tests</td>
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<td>MTS Pressing of Virgin Kraft Furnish</td>
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<td>4. Post pressing tests</td>
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<td>4. Verification</td>
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<td>2. Liquid movement in sheet</td>
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<td>Model Of Internal Sheet Processes</td>
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<td>4. Verification</td>
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<td>4. Testing</td>
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V. HOT PRESSING

A. Summary

The problem of describing hot pressing in a quantitative manner is extremely complicated. It is significantly more complicated than the steaming process because there is a dimensional change in the paper and there are also significant material property changes. A comprehensive model of the process would require the expenditure of significant resources. Such a model would be cumbersome to use and would provide more information than is required for tasks encompassed by this project. However, a model of some kind is required if a well coordinated study of the problem is to be made.

The goal in this study is to identify or develop a model which indicates quantitative correlations between incremental web preheating and changes in post pressing sheet properties. The work performed on this project can be used to develop a more comprehensive model at some future time. Listed below are some of the elements involved in the pressing of heated webs and some of the types of measurements which can be used to quantify the process.

PROCESS INPUT

- furnish
- solids
- sheet temperature
- roll temperature

Quantities measured prior to input

- finnish
- so lids
- sheet temperature
- roll temperature

- freeness
- permeability
- specific surface
- caliper
PROCESS (Heating then Pressing)

- mechanical load on sheet structure $f(t)$
- hydraulic load on fluid $f(t)$
- liquid velocity $f(t,z)$
- drag forces on sheet structure $f(t,z)$
- sheet compression during pressing $f(t)$
- sheet expansion at release of load $f(t)$

Quantities measured during process

- total applied load
- internal sheet temperatures
- platen temperature
- sheet caliper (?)

PROCESS OUTPUT

- Solids - water removal

Quantities measured after process

- ring crush
- ultrasound (ZD, CD, MD elastic modulus)
- STFI
- caliper
- permeability
- specific surface

These are the types of factors that will be considered in this project. It is proposed that the project follow two parallel paths, one experimental and one theoretical. The paths will complement one another. The experimental work provides data for verifying any model. By testing extreme cases, it provides some bounds to the theoretical study, and it also provides immediate data on trends that may be expected in actual machine operations. The theoretical study provides direction to the experimental work.
B. Hot Pressing - Experimental

The experimental work will investigate hot pressing of 42-lb sheets made from a 100% OCC furnish and a 100% Virgin Kraft furnish. These two furnishes represent extremes and should show different behaviors when subjected to pressing at elevated ingoing temperatures. The sheets will be pressed at three different ingoing solids levels (25%, 35%, 45%) and three different ingoing temperatures (ambient, ~60 °C, 90 °C). The three solids levels were chosen to roughly correspond to the levels existing prior to a 1st, 2nd, and 3rd press. The test plan includes testing of web properties before pressing, after pressing but prior to drying, and after drying. This was done so that correlations could be made between incremental web temperature increases and sheet properties at various points in the press section and at the reel. Sheet properties at various points in the press section are important when decisions are made about where to put a steambox or if more than one steambox is desirable. Properties at the reel are important from the standpoint of final product quality. The results of this testing will also provide data which can be used in a quantitative model. The literature does contain some experimental work on correlations between ingoing web temperature and outgoing web conditions. It does not contain data which is suitable for use in a quantitative model, nor does it address changes in permeability which appears to be of some importance in steaming.

Prior to pressing the following measurements will be made:

1. Water permeability
2. Air permeability
3. Caliper
4. Freeness.

The specific surface is calculated using the water permeability data. The specific surface results for the OCC furnish are presented in the next section.

After pressing, but before drying the following additional measurements will be made:
1. Water permeability
2. Air permeability
3. Caliper.

These measurements are made to evaluate changes in web properties that could be expected by placing a steambox at various points in the press section.

After pressing the samples will be finished dried under constraint. The samples will then be conditioned and subjected to the following tests:

1. Ultrasound MD, CD, ZD
2. STFI
3. Air Permeability.

Because of the difference in sample size required for air permeability, water permeability, STFI and ring crush, the ring crush test was eliminated from the test plan. A 1-in x 6-in sample is needed for ring crush tests, whereas all the other tests can be performed on a standard 4-in diameter sample. Producing a sample suitable for all tests requires manufacturing new platens. Using platens of different sizes to produces samples for all the tests introduces the problem of matching pressing profiles. This is extremely difficult given the current equipment.

C. Permeability Results

1. Summary

The first step in the pressing study was to obtain permeability data on the two furnishes at various moisture levels. An OCC furnish was tested first. The Virgin Kraft furnish has not been delivered at this time. However, it is expected to be delivered by 1 March 1996.

The OCC pulp was fractionated into long and short fibers prior to delivery to IPST. The nominal mixture when used for linerboard production with this furnish is 50% short fiber and 50% long fiber. Water permeability tests were carried out for the 42-lb sheets
produced from the short and long OCC fibers and a 50-50 mixture of short and long fibers on the Formette Dynamique. Only sheets made from the 50-50 mixture will be pressed. All sheets were formed using a forming and drain speed of 1800 m/min. The Canadian Standard Freeness for the long fibers was 386 ml CSF. The freeness for the short fiber sheets was 450 ml CSF. After being formed on the Formette, the sheets were pressed on a Baldwin Press to consistency 25% (1500 lbs, 15 seconds). One third of the sheets were left in this condition. The remaining sheets were pressed on a low-speed laboratory roll press to consistencies of 35 and 45%.

2. Evaluation and Testing of Deaeration Procedures

The usual procedure before a permeability test is to immerse the sheet in water for 30 minutes. This allows the water to penetrate completely into the sheet and remove the air from the sheet. In the case of the tested OCC sheets air removal did not occur. Despite soaking for 10 hours there was sufficient air remaining in the sheets for the sheets to float. In addition air bubbles were observed attached to the surface of the sheets. This result had not been observed with any previous furnish.

The first question to be answered was - Does the permeability remove most of the air from the sheet. Several sheets were tested despite showing air bubbles on the surface. After the permeability test, the sheets were immersed in water. The sheets sank. No air bubbles were present on the surface. This indicated that there was little or no air remaining in the sheet.

Given this initial result, a short study was performed to investigate the effect of air inside the sheet and air in the water used for the permeability test. Several of the 35% consistency sheets were used for this study. Each sheet was subjected to two permeability tests. In one test the water used was deaerated deionized water and in the
other deionized water from the tap. The results are tabulated in Table 1, shown on the following page.

The primary result was that the second test produced specific surface areas which were significantly less than those from the first test. This may be explained by removal air bubbles during the first test, confirming the importance of removing air from the sheet. This result is also stated in the work of Ceckler and Thompson [1], where it is emphasized that if deaeration of the apparatus (permeability cell) and the sheet is not properly carried out, a strong reduction of flow occurs during permeability measurements. Although deionized water used for the water permeability testing was deaerated, the importance of this step was not underscored by Ceckler and Thompson in [1].

**Table 1. Air in Sheet Tests**

<table>
<thead>
<tr>
<th>Sheet</th>
<th>Water Used</th>
<th>Test</th>
<th>Specific Surface $m^2/g$</th>
<th>$R^2$</th>
<th>Specific Volume $cm^3/g$</th>
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</thead>
<tbody>
<tr>
<td>M235</td>
<td>Deaerated</td>
<td>First</td>
<td>51.2</td>
<td>0.919</td>
<td>1.194</td>
</tr>
<tr>
<td>M535</td>
<td>Deaerated</td>
<td>First</td>
<td>53.7</td>
<td>0.966</td>
<td>1.114</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>52.5</strong></td>
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</tr>
<tr>
<td>M335T</td>
<td>Tap</td>
<td>First</td>
<td>36.7</td>
<td>0.966</td>
<td>1.41</td>
</tr>
<tr>
<td>M435T</td>
<td>Tap</td>
<td>First</td>
<td>46.5</td>
<td>0.96</td>
<td>1.17</td>
</tr>
<tr>
<td><strong>Average</strong></td>
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<td></td>
<td><strong>41.6</strong></td>
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</tr>
<tr>
<td>M235T</td>
<td>Tap</td>
<td>Second</td>
<td>17</td>
<td>0.972</td>
<td>1.741</td>
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<tr>
<td>M535T</td>
<td>Tap</td>
<td>Second</td>
<td>17.5</td>
<td>0.977</td>
<td>1.67</td>
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<tr>
<td><strong>Average</strong></td>
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<td></td>
<td><strong>17.3</strong></td>
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<tr>
<td>M335</td>
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<td>Second</td>
<td>17.5</td>
<td>0.982</td>
<td>1.695</td>
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<td>M435</td>
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<td>Second</td>
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<td>0.986</td>
<td>1.698</td>
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<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>18.1</strong></td>
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</tbody>
</table>

The tests also showed that the use of deaerated water is significant. This is seen by taking the average of the deaerated results (35.2 $m^2/g$) and the average of the tap water results (29.4 $m^2/g$) and comparing the two. In addition, it is seen that for the sheets being tested
for the first time, use of the tap non deaerated water resulted in a decrease of specific surface. This was somewhat unexpected. It is difficult to say whether this is a result of some physical regularities or stochastic result, since the data is based on only two tests. It seems also that the use of deaerated water resulted in lower variability of specific surface. For the sheets being tested a second time (without air bubbles), the difference when using deaerated and tap nondeaerated water was negligible. Note that all previous tests with this apparatus were carried out using deaerated water. These results showed that removing air from the sheet prior to the permeability test is critical to obtaining consistent results. The question remained as to how best remove air from the OCC sheets.

It was decided to remove the air from the OCC sheets prior to each test by subjecting the sheet to a low vacuum for an extended period of time. The vacuum must be low enough so that the water does not boil. If the water boils it would disrupt the sheet structure. It was assumed that if the sheet sank in water, the amount of air in the sheet was negligible and the sheet could be tested. The wet sheets were sandwiched between two screens taken from a 6 inch diameter British Handsheet Mold, this "sandwich" was placed into a vessel. Deaerated water was then poured into the vessel until the screens were submerged. The vessel was put into a desiccator under a vacuum of 15 in Hg. It was determined that a vacuuming time of 2 hours lead to sufficient removal of air from the sheet. The time was established by vacuuming for a period of time, removing the sheet from between the screens and determining if the sheet sank when not restrained. The vacuum time was extended until the sheet sank. As a further test of the vacuuming procedure a number of sheets were kept under vacuum for 12-15 hours. These were all sheets of 35% consistency. The specific surfaces values determined in theses tests are given in Table 2, on the following page.

The primary result of this study is that deaeration of the samples before the permeability test produces more consistent results for specific surface (see, for example Orloff, Phelan, Rudman [2]). The coefficient of variation of specific surface area is less than 20% for all cases. The maximum values of specific surface were about 40. This is evidence of a
A large concentration of fines in the pulp, which in turn causes large variability in specific surface (Ingman, Andrews, [3]). The same variability in permeability properties is obtained when using standard TAPPI Gurley Porosity test for air permeability of dry sheets. For comparison, the coefficient of variation of specific surface for the sheets not being deaerated (Orloff, Phelan, Rudman [2]) was of the order of 30-50% and more.

Table 2. Specific Surface (m²/g) Determined from Deaeration Tests

<table>
<thead>
<tr>
<th>Fiber and Preparation</th>
<th>35% Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long Fibers, Not Deaerated</td>
<td>44.1</td>
</tr>
<tr>
<td>Long Fibers, Deaerated 2 hrs</td>
<td>34.3</td>
</tr>
<tr>
<td>Long Fibers, Deaerated 15 hrs</td>
<td>22.8</td>
</tr>
<tr>
<td>Mixed Fibers, Not Deaerated</td>
<td>52.5</td>
</tr>
<tr>
<td>Mixed Fibers, Deaerated 2 hrs</td>
<td>27.4</td>
</tr>
<tr>
<td>Mixed Fibers, Deaerated 15 hrs</td>
<td>19.2</td>
</tr>
<tr>
<td>Short Fibers, Not Deaerated</td>
<td>-</td>
</tr>
<tr>
<td>Short Fibers, Deaerated 2 hrs</td>
<td>19.1</td>
</tr>
<tr>
<td>Short Fibers, Deaerated 15 hrs</td>
<td>15.8</td>
</tr>
</tbody>
</table>

3. OCC Permeability Test Results

Given the results of the deaeration study the following procedures were adopted:

1. Place sheet between Hand Sheet Mold screen and submerge in deaerated water.
2. Subject sheet to a vacuum of 15 in Hg for a period of 2 hours.
3. After vacuuming, soak sheet in deaerated water for 20 minutes.

4. Perform water permeability test as per nominal procedures.

All the OCC Sheets were tested using this procedure. The only exception was that the sheets having consistency 25%, were not soaked 20 minutes prior to the permeability test. Soaking caused these sheets to fall apart. The specific surfaces determined from these tests are summarized in Table 3.

Table 3. OCC Specific Surface (m²/g)

<table>
<thead>
<tr>
<th>Consistency, %</th>
<th>25% Solids</th>
<th>35% Solids</th>
<th>45% Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long Fiber, Deaerated 2 hrs</td>
<td>36.4</td>
<td>34.3</td>
<td>14.0</td>
</tr>
<tr>
<td>Mixed Fiber, Deaerated 2 hrs</td>
<td>31.2</td>
<td>27.4</td>
<td>11.6</td>
</tr>
<tr>
<td>Short Fiber, Deaerated 2 hrs</td>
<td>25.0</td>
<td>19.1</td>
<td>8.5</td>
</tr>
</tbody>
</table>

The averaged values of specific surface reasonably correlate with freeness and consistency. While specific surface is a higher resolution measurement than freeness, in general, when considering a single fiber source specific surface decreases with increased freeness and consistency. The results of all the tests are tabulated in Appendix D.

D. Hot Pressing - Quantitative Model

The goal of the Hot Pressing portion of this project is to develop a quantitative means of predicting the effects of incremental increases in web temperature just prior to entering the press. These effects can take the form of increases in outgoing solids at the press exit, increases in outgoing solids at the end of the press section, changes in web permeability at the press exit, changes in web caliper at the press exit, and changes in the
web final properties. The effects will vary with furnish. A model which produces a furnish dependent, quantitative results can be used to determine if and where in the press section web preheating should be used.

A review of the literature is in progress. At this time, most of the models found in the literature use extensive simplifications, are computational intensive or do not explicitly take into account ingoing web temperature. The intent of the literature search is to identify a modeling approach which can be used to predict, based on furnish, the effects of incremental web temperature increases. The approach selected will specifically address the web temperature effects, but will also be suitable for future expansion into a general pressing model. A finite element type model is not considered desirable, an analytically based model is more desirable as it provides insight into the physical processes taking place. No such models have been identified at this time.

D. Planned Work

1. Overview

Listed below are the research objectives for the next 24 months. This plan is somewhat ambitious, given that the required personnel have other commitments outside of this project. It is anticipated that in June this schedule will be re-evaluated. At that point in time there will be a significant amount of experimental data available and some theoretical data available. The purpose of the re-evaluation is to ensure that the approaches taken are the proper ones for attaining the stated goals of this project.
## 2. Schedule - continued

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APPENDIX A

Conduction Contribution

By considering transient conduction in a semi-infinite solid, it is possible to gain an “order of magnitude” understanding of how long it takes conduction to act in the paper web.

Transient Conduction Equation

\[ T(x,t) = \text{erf} \left( \frac{l}{2\sqrt{\alpha t}} \right) (T_1 - T_2) + T_2 \]

where

\( \alpha \) - thermal diffusivity, 0.000000123 m²/s.
\( x \) - distance into solid, .0007 m.
\( T_1 \) - initial temperature of the solid body, 20 °C.
\( T_2 \) - temperature at surface of solid body, 100 °C.
\( T(x,t) \) - transient temperature in the solid.

The value of thermal diffusivity is an estimate and was taken from Mark Strand, *Design and Development of a Device for the Measurement of Moist Paper Web Thermal Conductivity*, Master’s Thesis IPST, 1995. The results produced by the above equation are shown in Table A1 on the following page.
Table A1 - Transient Conduction Heat Flow Semi-Infinite Solid

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<th>Time (seconds)</th>
<th>( \frac{x}{2\sqrt{at}} )</th>
<th>( \text{erf}\left(\frac{x}{2\sqrt{at}}\right) )</th>
<th>T(x,t) (Deg C)</th>
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<td>0.974</td>
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APPENDIX B

Initial Calculation of Vapor Velocity

By considering some "typical" web properties, it is possible to gain an "order of magnitude" understanding of whether it is possible for steam to penetrate completely through the sheet. Taking the momentum equation for vapor (13)

$$\frac{\partial}{\partial t} (\rho, u_x) + \frac{\partial}{\partial z} (\rho, u_z) + \frac{\mu_x u_x}{K} = 0$$  \hspace{1cm} (17)

and assuming a linear pressure gradient given by $\Delta P / l$, where $l$ is the web thickness and $\Delta P$ is the pressure differential across the web gives

$$\frac{\partial}{\partial t} (\rho, u_x) + \frac{\mu_x u_x}{K} + \frac{\Delta P}{l} = 0.$$  \hspace{1cm} (18)

The general solution for (18) given an initial condition of $\rho, u_x(0)=0$ is

$$u_x(t) = \left[ \frac{\Delta P}{\mu_x l} \right] \left[ 1 - e^{(\mu_x)/\rho \cdot k} \right]$$  \hspace{1cm} (19)

Typical values for the above parameters are

- $K = 1 \times 10^{-14}$ m$^2$
- $l = 0.7 \times 10^{-3}$ m
- $\mu = 12.1 \times 10^{-6}$ kg/m-s
- $\rho = 0.605$ kg/m$^3$
- $\Delta P = 2$ psig

The time required for the steam vapor to go through the sheet is the maximum velocity times the thickness of the sheet. The maximum velocity is given by

$$u_{max}(t) = \left[ \frac{\Delta P}{\mu_x l} \right]$$

and has a value of 0.00826 m/s. Multiplying this by the sheet thickness gives a time of 0.043 sec. At a web speed of 2000 fpm the dwell time under a 18-in long steambox is 0.045 sec.
Therefore the conclusion is that it is theoretically possible for the steam to go through the sheet. Exact material properties and sheet caliper will determine if it does go through. It is probably necessary to experimentally verify this conclusion. Such an experiment can also serve as one means of verifying the assumption of Darcian flow.
Appendix C
II-in Cover, Full Vacuum

Weighted Average Temperature for Trials 1, 2, & 3

Trial #1
Trial #2
Trial #3
Avg

Time (sec)

Temperature (°C)
11-in Cover, Full Vacuum
Trial #2
II-in Cover, Full Vacuum Trial #3

11-in Cover, Full Vacuum Trial #3

Temperature (°C)

Time (sec)
20-in Cover, Full Vacuum
Weighted Average Temperature for Trials 1, 2, & 3
I,

20-in. Cover, Full Vacuum
Trial #3

TC1  TC2  TC3  TC4  TC5  TC7  Tavg

Temperature (°C)

Time (sec)
Appendix D

The results from the permeability tests are presented in Tables D1, D2, D3, D4 and D5. The first letter in the sheet designation stands for the pulp: L is for sheets made from long fibers; S is for short fibers; M is for the 50-50 mixture of long and short fibers. The digit after first letter stands for the number of the sample cut from a 12-in section of a single Formette sheet. Eight samples were cut from each section. The last two digits characterize the consistency of sheets.

Table D1 - Long Fiber Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Consistency, %</th>
<th>Freeness, ml CSF</th>
<th>Specific Surface, m²/g</th>
<th>R²</th>
<th>Specific Volume, cm³/g</th>
<th>Notes</th>
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</tr>
<tr>
<td>MV135</td>
<td>35</td>
<td>28</td>
<td>0.983</td>
<td></td>
<td>1.719</td>
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<tr>
<td>MV235</td>
<td>35</td>
<td>27.6</td>
<td>0.985</td>
<td></td>
<td>1.629</td>
<td>Deaer, tested</td>
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<tr>
<td>MV335</td>
<td>35</td>
<td>22.6</td>
<td>0.989</td>
<td></td>
<td>1.764</td>
<td>Deaer, tested</td>
</tr>
<tr>
<td>Ave</td>
<td></td>
<td>27.4</td>
<td></td>
<td></td>
<td>1.593</td>
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<tr>
<td>StdDev</td>
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<td></td>
<td>0.165</td>
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<tr>
<td>M145</td>
<td>45</td>
<td>11</td>
<td>0.986</td>
<td></td>
<td>2.148</td>
<td>Deaer, tested</td>
</tr>
<tr>
<td>M245</td>
<td>45</td>
<td>11.2</td>
<td>0.985</td>
<td></td>
<td>1.88</td>
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<tr>
<td>M345</td>
<td>45</td>
<td>9.7</td>
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<td></td>
<td>1.952</td>
<td>Deaer, tested</td>
</tr>
<tr>
<td>MV145</td>
<td>45</td>
<td>15.5</td>
<td>0.989</td>
<td></td>
<td>1.669</td>
<td>Deaer, tested</td>
</tr>
<tr>
<td>MV245</td>
<td>45</td>
<td>10.8</td>
<td>0.982</td>
<td></td>
<td>1.881</td>
<td>Deaer, tested</td>
</tr>
<tr>
<td>Ave</td>
<td></td>
<td>11.6</td>
<td></td>
<td></td>
<td>1.906</td>
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<tr>
<td>StdDev</td>
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<td>2.2</td>
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<td></td>
<td>0.172</td>
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Table D5 - Short Fiber Samples

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<thead>
<tr>
<th>Sample</th>
<th>Consistency, Freeness, ml CSF</th>
<th>Specific Surface, m²/g</th>
<th>R²</th>
<th>Specific Volume, cm³/g</th>
<th>Notes</th>
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<tbody>
<tr>
<td></td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S235</td>
<td>35</td>
<td>450</td>
<td>15.8</td>
<td>0.989</td>
<td>1.929 Deaer, 12h in</td>
</tr>
<tr>
<td>S335</td>
<td>35</td>
<td>450</td>
<td>17.9</td>
<td>0.989</td>
<td>1.827 Deaer, 12h in</td>
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<tr>
<td>S835</td>
<td>35</td>
<td>450</td>
<td>13.8</td>
<td>0.984</td>
<td>1.641 Deaer, 12h in</td>
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<td>Ave</td>
<td></td>
<td></td>
<td>15.8</td>
<td></td>
<td>1.799</td>
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<tr>
<td>S735</td>
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<td>450</td>
<td>19.5</td>
<td>0.983</td>
<td>1.576 Deaer, tested</td>
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<tr>
<td>S635</td>
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<td>450</td>
<td>18.1</td>
<td>0.989</td>
<td>1.462 Deaer, tested</td>
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<tr>
<td>S535</td>
<td>35</td>
<td>450</td>
<td>15.6</td>
<td>0.953</td>
<td>1.968 Deaer, tested</td>
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<tr>
<td>S435</td>
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<td>450</td>
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<td>0.954</td>
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<tr>
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<td>450</td>
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<td>450</td>
<td>8.9</td>
<td>0.987</td>
<td>1.872 Deaer, tested</td>
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<tr>
<td>S245</td>
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<td>450</td>
<td>8.5</td>
<td>0.972</td>
<td>1.898 Deaer, tested</td>
</tr>
<tr>
<td>S345</td>
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<td>450</td>
<td>8.3</td>
<td>0.98</td>
<td>1.9 Deaer, tested</td>
</tr>
<tr>
<td>SV145</td>
<td>45</td>
<td>450</td>
<td>7.9</td>
<td>0.982</td>
<td>1.885 Deaer, tested</td>
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<tr>
<td>SV245</td>
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<td>450</td>
<td>8.9</td>
<td>0.975</td>
<td>1.805 Deaer, tested</td>
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<tr>
<td>Ave</td>
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<td></td>
<td>8.5</td>
<td></td>
<td>1.872</td>
</tr>
<tr>
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<td></td>
<td>0.4</td>
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<td>0.039</td>
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2. Cansler, D. Steam Box Analysis. A Thesis Submitted to the Faculty of the EPMD in Candidacy for the Degree of Master of Science (June, 1995)
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Other Authors
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Vacuum Dewatering: Edward DeCrosta, M. R. Green

Literature: Permeability


Literature: Pressing


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WILL ADVISE ON THE FILINGS.

FUNDAMENTALS OF DRYING

STATUS REPORT

FOR

PROJECT F001

David I. Orloff

March 18 - 19, 1996

Institute of Paper Science and Technology
500 10th Street, N.W.
Atlanta, Georgia 30318
TECHNICAL PROGRAM REVIEW

Project Title: FUNDAMENTALS OF DRYING
Project Code: DRYING
Project No.: F001
Division: Engineering and Paper Materials
Project Staff: David Orloff, Timothy Patterson, Issak Rudman
Budget (FY95-96): $360,700
Government Funding: To IPST: FY95-96 $287,000 FY96-97 $700,000
M.S. Students: FY95-96 One

I. OBJECTIVE

To develop an understanding and a database for commercialization of advanced water removal systems, based on high-intensity drying principles. This new technology will reduce capital costs, increase machine productivity, reduce Virgin fiber use, reduce the amount of energy used, and improve physical properties.

II. GOAL

To commercialize the impulse drying process by 1998 and expand its operating window to include a wider range of furnishes, basis weights, and grades.

III. SUMMARY

Work on the dues-funded (No. F001) project and on the separate DOE-funded (No. 3595) project is on track. The dues-funded work has focused on developing fundamental
understanding that would open the grade-furnish-basis weight operating window of
impulse drying. The DOE-funded work (with financial support from Beloit) is currently
concentrated on roll surface durability and the design and installation of a pilot impulse
dryer on Beloits' No. 4 pilot paper machine. The key accomplishments of this period are
summarized here.

Project No. F001:

- Discovered that opening the nip to high “ambient” pressures may be used to
  eliminate sheet delamination of highly refined, low ingoing solids, high basis
  weight sheets. A U.S. patent has been filed.

- Discovered that delamination can also be suppressed by modifying the nip
decompression rate during nip opening. A U.S. patent is in preparation.

- Developed a thermodynamic model of evaporation during nip opening. Theory
  has been compared to experiments and has been used to help identify the
  operating mechanisms involved in the modified nip decompression
  experiments.

Project No. 3595:

- Negotiated agreements with Beloit regarding the commercialization of IPST
  impulse drying technology for board grades.

- Obtained DOE funding and Beloit involvement and contributions for the first
  year of a two-year continuous high-speed pilot impulse drying development and
  evaluation project.

- As part of the objectives for the first year, IPST is preparing four roll coatings
  for evaluation on the IPST impulse drying durability test facility.

As part of the objectives for the first year, Beloit has completed the design of an induction
heating system to be installed on its No. 4 paper machine.
IV. DISCUSSION

Background:

Previous impulse drying research has focused attention on the processes occurring while the sheet is in the press nip, but very little effort has been expended in understanding the phenomena occurring as the nip opens. Starting in 1994, the Institute began preparing to extend its impulse drying research into this unexplored territory. This was made manifest with the construction of a new laboratory scale impulse drying simulator that would allow improved control of the applied load-versus-time curve and would allow control of the ambient pressure, which the nip opens to as well as the postnip cooling rate. Recent research has led to an important discovery that by increasing the ambient pressure at nip opening, the maximum roll temperature, as limited by sheet delamination, can be significantly increased. Additional research has also shown that the rate of pressure drop and heat transfer during nip opening are important factors in controlling internal steam flashing and sheet delamination.

Experimental Impulse Drying Results:

High Ambient Pressure Impulse Drying:

Figure 1 shows the laboratory scale high ambient pressure impulse dryer (HAPID) that was constructed. The system is a modification to the impulse drying head that was previously attached to the MTS testing machine. The new device allows the nip to open to any desired gas pressure and temperature.
Figure 1. Laboratory Scale High Ambient Pressure Impulse Dryer.

In typical applications, the HAPID unit functions similarly to the previous MTS impulse dryer with the exception that midway during the 40 ms press impulse a valve is rapidly opened, which allows Nitrogen gas to fill the chamber surrounding the impulse dryer to a prescribed gas pressure. Figure 2 shows typical load and gas pressure versus time during a HAPID experiment.
The impulse dried sheet experiences a higher than normal ambient pressure as it comes into contact with the surrounding high pressure gas. Figure 3 shows the pressure that the sheet would experience if it opened to an ambient pressure of 1000 kPa absolute (131 psig).

Figure 3. Load Pressure as Experienced by a Sheet Impulse Dried in the HAPID Apparatus at an Ambient Pressure of 1000 kPa (absolute).
As part of his A190 project, Andy Krause conducted the first experiments using the HAPID apparatus. In his experiments, Andy impulse dried an unbleached southern pine Kraft that had been refined to 400 ml CSF, formed into a single-ply 42 lb/1000 ft² (205 g/m²) sheet and prepressed to 35% solids. In the prepressed state, these sheets had a specific surface of 29.5 m²/g. Impulse drying was accomplished with a steel platen. Sheets were preheated to 85 C just prior to impulse drying. In a typical HAPID experiment, the platen set-point temperature was fixed, then similar sheets were impulse dried at successively higher ambient pressures until the sheet did not delaminate. At a given set-point platen temperature, the ambient pressure above which delamination was suppressed was termed the critical ambient pressure corresponding to that platen set-point temperature. Table 1 shows these critical ambient pressures.

Table 1. Critical Ambient Pressure from HAPID Experiments.

<table>
<thead>
<tr>
<th>Case</th>
<th>Platen Set-Point Temperature, C</th>
<th>Critical Ambient Pressure, kPa (abs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>~110</td>
</tr>
<tr>
<td>2</td>
<td>175</td>
<td>152</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>170</td>
</tr>
<tr>
<td>4</td>
<td>260</td>
<td>315</td>
</tr>
<tr>
<td>5</td>
<td>330</td>
<td>411</td>
</tr>
</tbody>
</table>

Of major significance, these experiments showed that by opening the impulse drying nip to elevated ambient pressures, the platen temperature could be significantly increased without experiencing sheet delamination. The experiments further showed that water removal was independent of ambient pressure and linearly dependent on platen temperature. This result is shown graphically, in Figure 4.
Of even more importance, Krause's data showed that as the platen temperature was increased, the STFI compression strength of the sheet increased until it reached what appeared to be a maximum value. See Figure 5.

Figure 4. Moisture Ratio Change As A Function Of Platen Temperature.

Figure 5. STFI Compression Strength of Sheets Impulse Dried at the Critical Ambient Pressures Corresponding to the Specified Platen Temperatures.
In subsequent experiments, critical ambient pressure was determined for a wider range of basis weight, ingoing solids, and freeness. These results are shown in Table 2, and have been included with those of Krause in a recent IPST U.S. patent application (May 1995).

Table 2.


<table>
<thead>
<tr>
<th>B.Wt</th>
<th>%Sin</th>
<th>Freeness</th>
<th>Pcrit</th>
</tr>
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<tbody>
<tr>
<td>#/1000 sqft</td>
<td>ml CSF</td>
<td>kPa (abs)</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>50</td>
<td>700</td>
<td>~201</td>
</tr>
<tr>
<td>90</td>
<td>25</td>
<td>700</td>
<td>231</td>
</tr>
<tr>
<td>90</td>
<td>50</td>
<td>400</td>
<td>521</td>
</tr>
<tr>
<td>90</td>
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<td>700</td>
<td>101</td>
</tr>
<tr>
<td>26</td>
<td>50</td>
<td>400</td>
<td>271</td>
</tr>
<tr>
<td>26</td>
<td>25</td>
<td>400</td>
<td>201</td>
</tr>
</tbody>
</table>

As in the earlier Krause experiments, it was shown that by opening the nip to high enough ambient pressure, delamination could be avoided. In order to implement HAPID, the IPST patent application suggested a number of equipment modifications. Included was the idea of using a high velocity air knife at the nip exit, between the press roll and sheet, to induce a higher than normal ambient pressure.

While this concept may prove to be practical, other less drastic measures were targeted for further proof-of-principle experiments.

Controlled Decompression (Nip-Opening Ramp) Impulse Drying:

Modifying the decompression profile during nip opening was one of the alternate concepts that was tried. In this concept, the ambient pressure surrounding the impulse dryer would
be maintained at one atmosphere (101 kPa absolute), while the nip-opening pressure profile would be modified by adding a shallow slope ramp profile. Such a ramp profile extension was believed to be practically implemented by an appropriate post impulse drying roll wrap. Figure 6 shows the ramp decompression profiles that were investigated.

![Typical Ramp Load Pressure Profiles](image_url)

Figure 6. Nip-opening Decompression Profiles.

Using the same handsheets as were used in Krause's experiment, a series of impulse drying experiments were performed in which all conditions were maintained constant, except the nip-opening decompression profile and platen set-point temperature. Figure 7 shows the increase in outgoing solids with increased platen set-point temperature. As the nip residence time and impulse both increase as the ramp was changed from the NO ramp to the A ramp, an observed increase in outgoing solids is understandable.
Figure 7. Average Outgoing Solids as a Function of Platen Set-Point Temperature for Four Nip-opening Ramp Profiles.

The sheets that were impulse dried in this way were tested using out-of-plane ultrasound. The coefficient of variation of the specific elastic modulus was determined and is shown plotted as a function of platen set-point temperature and ramp profile in Figure 8.
Figure 8. Average Coefficient of Variation of the Specific Elastic as a Function of Platen Set-Point Temperature for Four Nip-opening Ramp Profiles.

Following earlier work, delaminated sheets were found to have coefficients of variation in excess of between 10 and 15%. Review of Figure 8 showed that sheets impulse dried using the NO ramp delaminated at all platen set-point temperatures investigated. Ramp C only failed to delaminate at the lowest platen set-point temperature of 200 C, while ramps B and A prevented delamination at all platen set-point temperatures. While STFI compression testing has not been completed as yet, Figure 9 shows an increase in specific elastic modulus with increased platen set-point temperature for sheets that were produced with ramp B or ramp A. These results are being included as an improvement to the IPST patent applications.
Figure 9. Average Specific Elastic Modulus as a function of Platen Set-point Temperature for Four Nip-opening Ramp Profiles.

**Conceptual Understanding:**

The important lesson of these results is that sheet delamination can be controlled by adjusting the nip-opening process. This idea has led to an even broader, and potentially more useful result, that it is important to understand the thermodynamics of the nip-opening process.

Figure 10 shows a conceptual view of the moisture, pressure, and temperature profiles in a sheet that is undergoing impulse drying at an instant of time just prior to the start of nip opening. In the figure, the top surface of the sheet is in contact with the heated press roll, which acts as a heat source, while the bottom surface of the sheet is in contact with the press felt, which acts as a water reservoir. Sheet moisture is at its lowest value at the sheet-roll interface and at its highest value at the sheet-felt interface. Sheet temperature is at its maximum at the sheet-roll interface and at its minimum value at the sheet-felt interface. As a
result, there are three distinct regions of the sheet. In Region a, near the press roll surface, the pores of the sheet contain little water and are at high temperature. In Region b, in the middle of the sheet, the pores contain liquid water and are at moderately high temperatures (more than 100 C). In Region c, near the press felt, the pores contain substantial water and are at a low temperature (less than 100 C). In this conceptual model, only the pores in Region b of the sheet contain enough water and are at sufficiently high temperature to flash to vapor as the nip opens.

![Conceptual Moisture and Temperature Profile Just Prior to the Nip Opening](image)

As the nip opens, the pressure decreases with time until the heated surface of the sheet is no longer in contact with the heated press roll. During this time interval, the heated press roll continues to transfer heat to the sheet and, consequently, to the pores. This combination of pressure drop and heat transfer results in rapid flashing to vapor, of liquid contained in the pores of Region b, and also results in evaporative cooling.

It has been previously proposed that sheet delamination is the result of this flash evaporation process. If the sheet above region b were assumed (in the extreme case) to be
impermeable, flashing in the pores would result in sheet expansion and, if extensive enough, in inter-fiber bond failure. In the more realistic case, where the sheet above region \( b \) is permeable, flashing in the pores will result in both venting of flashed vapor, to the sheet-platen interface, and sheet expansion. In this case inter-fiber bond failure can occur at any time when the net forces on the sheet exceed the failure strength of region \( b \).

In either case, it is proposed here that the probability of delamination can be reduced by modifying the nip opening process to reduce the extent of internal expansion, to lengthen the time during which flashed vapor can escape from the sheet, or to reduce the forces on the sheet that lead to delamination. The intent of the following model is to develop an understanding of the variables that would be expected to influence these processes. The model assumes that the sheet is sufficiently impermeable such that there is no venting.

**Mathematical Model Of Nip Opening:**

Consider a pore in Region \( b \) of the sheet. The mass of water contained within that pore may be defined as a thermodynamic system. As the sheet is expected to increase in caliper as the nip opens, the boundaries of the thermodynamic system (pore) expands when the water within undergoes a change of phase. Figure 11 shows the thermodynamic system at the beginning of the process and at some later time during the process.
Figure 11. The Thermodynamic System.

In Figure 11, and in the following derivation, $m$ represents the system mass (water); $Q$ represents the heat transfer to the system from the surroundings; and $W$ represents the work done by the system on the surroundings. The following assumptions are introduced:

a. The mass of the system is conserved. There is no venting during nip depressurization.

b. The surface of the system expands with time, doing reversible work on the surroundings.

c. Heat is transferred from the surroundings to the system.

d. The pressure of the system, independent of its z-directional location in the sheet, is equal to the load pressure applied to the surroundings during nip opening.
At the beginning of depressurization, the thermodynamic system is at a pressure, $P_{\text{max}}$, and at a temperature, $T_{\text{max}}$. It is anticipated that $P_{\text{max}}$ may be higher than the saturation pressure, $P_{\text{sat}}$, corresponding to the temperature, $T_{\text{sat}}$. Hence, at the onset of depressurization, the system may be a subcooled liquid. In such a case, depressurization will proceed until the system becomes a saturated liquid. From that point on, continued depressurization results in vaporization with a subsequent substantial increase in volume. As a special case, $P_{\text{max}}$ may be equal to $P_{\text{sat}}$ so that the system starts off as a saturated liquid and vaporization proceeds immediately with depressurization.

If the starting pressure, $P_{\text{max}}$, were less than $P_{\text{sat}}$, then no vaporization would take place as the system would already be a superheated vapor. In that case, vaporization would take place in a pore that is located farther away from the heated surface of the sheet, at the saturation temperature, $T_{\text{sat}}$, corresponding to the starting pressure, $P_{\text{max}}$.

Figure 12 shows the process on a $T$-$v$ diagram. It is observed that the process may be separated into two regimes, a subcooled liquid regime, where the system volume increases slightly with a reduction in system pressure, and a saturated regime, where a system pressure decrease results in vaporization and a large increase in system volume.
Subcooled Regime:

In the subcooled regime, the specific volume of the system, \( v \), is a function of both system temperature, \( T \), and system pressure, \( P \).

\[ v = v(P, T) \quad \{1\} \]

Hence, changes in pressure and temperature will result in a change in the specific volume.

\[ dv = \left( \frac{\partial v}{\partial P} \right)_T dP + \left( \frac{\partial v}{\partial T} \right)_P dT \quad \{2\} \]

As the mass of the thermodynamic system, \( m \), is constant with respect to time, the rate of system volume increase can be written as,
\[ \frac{dV}{dt} = m \frac{dv}{dt} \]  \hspace{1cm} \{3\}

Substituting \{2\} into \{3\} yields,

\[ \frac{dV}{dt} = m \left( \frac{\partial v}{\partial P} \right)_T \frac{dP}{dt} + \left( \frac{\partial v}{\partial T} \right)_P \frac{dT}{dt} \]  \hspace{1cm} \{4\}

From the first law of thermodynamics, the heat transfer to the system must equal the sum of the change in internal energy of the system and the work done by the system on its surroundings.

\[ \frac{\delta Q}{dt} = \frac{dU}{dt} + \frac{\delta W}{dt} \]  \hspace{1cm} \{5\}

The internal energy of the system is

\[ U = mu \]  \hspace{1cm} \{6\}

Hence, the rate of increase in the system internal energy is

\[ \frac{dU}{dt} = m \frac{du}{dt} = m \left[ \left( \frac{\partial u}{\partial P} \right)_T \frac{dP}{dt} + \left( \frac{\partial u}{\partial T} \right)_P \frac{dT}{dt} \right] \]  \hspace{1cm} \{7\}

The reversible work done by the system on the surroundings is
\[
\frac{\delta W}{dt} = P \frac{dV}{dt}
\]  

\{8\}

Substituting \{4\} into \{8\} yields

\[
\frac{dW}{dt} = Pm \left[ \left( \frac{\partial v}{\partial P} \right)_T \frac{dP}{dt} + \left( \frac{\partial v}{\partial T} \right)_P \frac{dT}{dt} \right]
\]  

\{9\}

Combining \{9\} and \{7\} into \{5\} results in

\[
\frac{\delta Q}{dt} = m \left\{ \left( \frac{\partial u}{\partial P} \right)_T + P \left( \frac{\partial v}{\partial P} \right)_T \right\} \frac{dP}{dt} + \left\{ \left( \frac{\partial u}{\partial T} \right)_P + P \left( \frac{\partial v}{\partial T} \right)_P \right\} \frac{dT}{dt}
\]  

\{10\}

Solving for the rate of change of temperature,

\[
\frac{dT}{dt} = \frac{1}{m} \frac{\delta Q}{dt} - \left\{ \left( \frac{\partial u}{\partial P} \right)_T + P \left( \frac{\partial v}{\partial P} \right)_T \right\} \frac{dP}{dt}
\]  

\{11\}

We may now substitute \{11\} into \{4\} to obtain the increase in volume of the system.

**Saturated Regime:**

In the saturated regime, the mass of liquid water, \(m_L\), may decrease with time, and the mass of water vapor, \(m_v\), may increase with time. Yet, the total mass of water, contained within the system boundaries, must remain constant. Hence, from continuity,
Differentiating with respect to time,

\[
\frac{dm}{dt} = \frac{dm_L}{dt} + \frac{dm_v}{dt} = 0 \tag{13}
\]

Hence, the rate of loss of liquid water, \(m_L\), is equal and opposite in sign to the rate of increase of water vapor, \(m_v\).

\[
\frac{dm_L}{dt} = -\frac{dm_v}{dt} \tag{14}
\]

The system volume may be calculated from the volume of the liquid water and water vapor contained within the system boundaries.

\[
V = m_L v_f + m_v v_g \tag{15}
\]

Differentiating with respect to time,

\[
\frac{dV}{dt} = m_L \frac{dv_f}{dt} + v_f \frac{dm_L}{dt} + m_v \frac{dv_f}{dt} + v_f \frac{dm_v}{dt} + v_g \frac{dm_v}{dt} \tag{16}
\]

The rate of increase in system volume can be simplified by recognizing that \(v_f\) and \(v_g\) are both only functions of pressure (note: \(v_f = v_g - v_f\)), and by using (14),

\[
\frac{dV}{dt} = v_g \frac{dm_v}{dt} + \frac{dP}{dt} \left[ (m - m_v) \frac{dv_f}{dP} + m_v \frac{dv_g}{dP} \right] \tag{17}
\]
Where \( \frac{dP}{dt} \) is the rate of change of the system pressure.

Again, from the first law of thermodynamics,

\[
\frac{\delta Q}{dt} = \frac{dU}{dt} + \frac{\delta W}{dt}
\]

Where the system internal energy, \( U \), is given by

\[
U = m_L u_f + m_v u_g
\]

Noting that \( u_g = u_e - u_f \), we may write the rate of change of the system internal energy as

\[
\frac{dU}{dt} = u_f \frac{dm_v}{dt} + \frac{dP}{dt} \left[ m \frac{du_f}{dP} + m_v \frac{du_g}{dP} \right]
\]

Assuming that all of the work done by the system is reversible boundary expansion work,

\[
\delta W = PdV
\]

Hence,

\[
\frac{\delta W}{dt} = P \frac{dV}{dt}
\]
Substituting \(17\) into \(22\) yields

\[
\frac{dW}{dt} = v_{fs}P \frac{dm_v}{dt} + P \frac{dP}{dt} \left[ m \frac{dv_f}{dP} + m_v \frac{dv_{fs}}{dP} \right]
\]

Combining \(23\), \(20\), and \(18\), we may solve for the evaporation rate

\[
\frac{dm_v}{dt} = \frac{\delta Q - \frac{dP}{dt} \left[ m \left( \frac{du_f}{dP} + P \frac{dv_f}{dP} \right) + m_v \left( \frac{du_{fs}}{dP} + P \frac{dv_{fs}}{dP} \right) \right]}{u_{fs} + v_{fs}P}
\]

Knowing the initial thermodynamic state of the system, and the rate of change of system pressure and the rate of heat transfer, as imposed by the surroundings, we may use \(24\) and \(12\) to predict the water vapor contained in the system as a function of time.

**Measurement Of Heat Flux:**

It was anticipated that heat flux would be a function of sheet specific surface, ingoing solids and temperature, impulse drying platen temperature, platen thermal properties, press impulse, and the nip-opening depressurization curve. To explore these anticipated dependencies, a series of impulse drying experiments were conducted in which initial platen surface temperature, \(T_{ps,0}\), and the nip-opening depressurization curve were systematically varied while the instantaneous heat flux was recorded.

The following conditions were maintained constant:
1. Sheet: Unbleached softwood Kraft refined to 400 ml CSF in a 205 g/m² single-ply machine directionally oriented sheet.

2. Ingoing Conditions: 34% solids preheated uniformly to 85 C.

3. Platen Materials: Steel, having a thermal mass of 7500 W s^12/m² C.

4. Impulse Drying Conditions: 40 ms square-pressure pulse having a peak pressure of 4.3MPa, followed by a variable-shaped decompression ramp profile.

The experiments were conducted at three platen set-point temperatures, Ts.p., of 200 C, 230 C, and 260 C, corresponding to three initial platen surface temperatures, Tp.s., of 184 C, 208 C, and 245 C, respectively. The experiments were also conducted using four nip-opening depressurization profiles, designated as ramps NO, C, B, and A. These ramps are shown in Figure 4.

![Ramp Depressurization Profiles](image-url)

Figure 13. Ramp Depressurization Profiles.
Heat flux was determined using a technique that the author has described in previous publications. This was accomplished by measuring the surface temperature of the steel platen throughout the impulse drying process using a specially constructed vacuum-deposited surface thermocouple. The measured temperature data and known values of thermal properties of the steel platen were then used to calculate heat flux in units of MW/m².

At each condition of initial platen temperature and depressurization profile, 10 replicate impulse drying experiments were run. Of these, four replicates at each condition have been analyzed as of the time of this writing (data from the additional six replicates will be added to improve the polynomial fits). In each, load pressure, platen surface temperature, and instantaneous heat flux were obtained every millisecond. Review of the data showed a consistent pattern that heat flux was linear with load pressure at low pressure and nearly constant at high pressure. The data also showed a nearly linear dependence on initial platen surface temperature. This pressure dependence, at low pressure, is reminiscent of contact resistance. Hence, the heat flux data may be best presented as plotted against pressure.
Figure 14. Heat Flux Times the Temperature Difference Between the Initial Platen Surface Temperature and the Ingoing Sheet Temperature for the Ramp=NO Nip-opening Decompression Profile at a Platen Set-point Temperature of 200 C.
Figure 15. Heat Flux Times the Temperature Difference Between the Initial Platen Surface Temperature and the Ingoing Sheet Temperature for the Ramp=NO Nip-opening Decompression Profile at a Platen Set-point Temperature of 230 C.
HF/DH = 8.0215e-4 + 7.6899e3P - 1.3934e-3P² - 1.2253e-3P³ + 4.9734e-4P⁴ - 5.1079e-5P⁵ R² = 0.822

Figure 16. Heat Flux Times the Temperature Difference Between the Initial Platen Surface Temperature and the Ingoing Sheet Temperature for the Ramp=NO Nip-opening Decompression Profile at a Platen Set-point Temperature of 260 C.
\[ \frac{HF}{DT} = -1.8756e-3 + 1.0344e-2P - 8.4109e-3P^2 + 2.9608e-3P^3 - 4.4523e-4P^4 + 2.2438e-5P^5 \]

\[ R^2 = 0.84 \]

Figure 17. Heat Flux Times the Temperature Difference Between the Initial Platen Surface Temperature and the Ingoing Sheet Temperature for the Ramp=C, Nip-opening Decompression Profile at a Platen Set-point Temperature of 200°C.
Figure 18. Heat Flux Times the Temperature Difference Between the Initial Platen Surface Temperature and the Ingoing Sheet Temperature for the Ramp= C, Nip-opening Decompression Profile at a Platen Set-point Temperature of 230 C.
Figure 19. Heat Flux Times the Temperature Difference Between the Initial Platen Surface Temperature and the Ingoing Sheet Temperature for the Ramp= C, Nip-opening Decompression Profile at a Platen Set-point Temperature of 260 C.
HF = - 7.5927e-4 + 5.0224e-3P - 2.7196e-3P^2 + 3.2059e-4P^3 + 8.8704e-5P^4 - 1.6306e-5P^5  \quad R^2 = 0.738

Figure 20. Heat Flux Times the Temperature Difference Between the Initial Platen Surface Temperature and the Ingoing Sheet Temperature for the Ramp= B, Nip-opening Decompression Profile at a Platen Set-point Temperature of 200 C.
Figure 21. Heat Flux Times the Temperature Difference Between the Initial Platen Surface Temperature and the Ingoing Sheet Temperature for the Ramp= B, Nip-opening Decompression Profile at a Platen Set-point Temperature of 230 C.
HF/DT = -1.3245e-4 - 6.2177e-3P + 1.7440e-2P^2 - 1.0838e-2P^3 + 2.6188e-3P^4 - 2.2146e-4P^5  \ R^2 = 0.868

Figure 22. Heat Flux Times the Temperature Difference Between the Initial Platen Surface Temperature and the Ingoing Sheet Temperature for the Ramp= B, Nip-opening Decompression Profile at a Platen Set-point Temperature of 260 C.
\[ \frac{dF}{dT} = -2.7925 \times 10^{-4} + 1.0860 \times 10^{-3}P + 3.2711 \times 10^{-2}P^2 - 3.2595 \times 10^{-3}P^3 + 1.0196 \times 10^{-4}P^4 - 1.0298 \times 10^{-5}P^5 \quad R^2 = 0.626 \]

Figure 23. Heat Flux Times the Temperature Difference Between the Initial Platen Surface Temperature and the Ingoing Sheet Temperature for the Ramp= A, Nip-opening Decompression Profile at a Platen Set-point Temperature of 200 C.
HF/DT = 1.5429e-4 - 6.1007e-3P + 1.5515e-2P^2 - 9.2886e-3P^3 + 2.1758e-3P^4 - 1.7865e-4P^5 \quad R^2 = 0.871

Figure 24. Heat Flux Times the Temperature Difference Between the Initial Platen Surface Temperature and the Ingoing Sheet Temperature for the Ramp= A, Nip-opening Decompression Profile at a Platen Set-point Temperature of 260 C.

It was also observed that heat flux at each pressure tends to increase when the time for nip opening is reduced. This was probably due to the fact that, holding initiate platen temperature constant while reducing nip opening time resulted in an increase in average platen surface temperature during nip opening. It was also noticed that negative heat flux was calculated for pressures below about 0.5 MPa. Whether this is an experimental error, or is real, will require future investigation. As these negative heat fluxes insignificantly impact the results of this report, they have been included in the fifth-order polynomial least squares fits that are presented with each figure.
Measurement of Internal Sheet Temperature:

The proposed thermodynamic model requires certain initial conditions and boundary conditions. The system depressurization profiles, dP/dt vs t, are assumed to be known, and these are assumed to equal the load depressurization rate. The rate of heat transfer to the system, dQ/dt, is the second boundary condition on the thermodynamic problem.

An estimate for the rate of heat transfer, see equation (25), may be determined from the measured heat flux curves of the last section, an estimate of the percent solids, %S, at Region b at nip opening and the basis weight of the sheet, Bwt. This equation allows the heat flux data, in MW/m², to be converted into heat transfer in units of MW/kg of the system. It is only an estimate because the actual rate of heat transfer should also account for conductive and convective heat transfer within the sheet.

\[
\frac{\delta Q}{dt} = \frac{\text{HeatFlux}}{(100 - \%S)(\%S)(Bwt)}
\]

With this estimate and the temperature of Region b at the beginning of nip opening, the thermodynamic model can be used to predict the vaporization of subcooled liquid water. To obtain this temperature, and to provide a check on some of the predictions of the model, additional impulse drying experiments were performed. In these experiments, which were otherwise identical to those presented in the last section, the sheets were formed from three equal layers with two thousands diameter thermocouples between layers and on the top and bottom surfaces of the sheet.

Figures 25 through 29 show these experimental temperature profiles. The temperature on the heated surface of the sheet is designated as T1, those between sheet layers as T2, and
T3, and on the surface of the sheet in contact with the felt as, T4. The platen set-point temperature, as measured and maintained constant by a thermocouple on the back side of the platen, is designated as Ts.p. The instantaneous platen surface temperature, as measured by a vacuum-deposited thermocouple, is designated as Tp.s.

From previous experience, it is anticipated that the region of the sheet, Region b, that is susceptible to delamination is within the upper third of the sheet. Hence, we can estimate an upper and lower bound for the temperature of Region b, at the start of decompression, as being between the initial values (at the onset of decompression) of T1 and T2. Table 3 lists these estimates, as well as the initial platen surface temperatures, Tp.s.i (at the onset of impulse drying) for the three platen set-point temperatures of the present experiments. These estimates will be used later in the theoretical analysis.

<table>
<thead>
<tr>
<th>Ts.p. Platen Set-point Temperature, C</th>
<th>Tp.s.i Initial Platen Surface Temperature, C</th>
<th>T1i Initial Temperature of Top of Sheet, C</th>
<th>T2i Initial Temperature of One-Third From Top of Sheet, C</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>184</td>
<td>165</td>
<td>105</td>
</tr>
<tr>
<td>230</td>
<td>208 (Not Measured)</td>
<td>Not Measured</td>
<td>(Not Measured)</td>
</tr>
<tr>
<td>260</td>
<td>245</td>
<td>200</td>
<td>125</td>
</tr>
</tbody>
</table>

Table 3. Temperature Estimates.
Figure 25. Measured Temperature as a Function of Time During Nip Opening Using Ramp NO. at a Set-point Temperature of 200°C.

Figure 26. Measured Temperature as a Function of Time During Nip Opening Using Ramp NO. at a Set-point Temperature of 260°C.
Figure 27. Measured Temperature as a Function of Time During Nip Opening Using Ramp C, at a Set-point Temperature of 200°C.

Figure 28. Measured Temperature as a Function of Time During Nip Opening Using Ramp A, at a Set-point Temperature of 200°C.
A number of important observations can be made from the experimental temperature profiles. These are

1. The platen surface temperature was normally higher than the temperature of the top surface of the sheet throughout decompression. The existence of such a difference implies that there is water vapor contained at the interface between the sheet and the platen. This is also consistent with the analogy to contact resistance, as suggested in the heat flux section, and strongly supports the idea that venting actually does occur.

2. The temperature of the top surface of the sheet, as well as the interface temperature between the top layer and middle layer of the sheet, generally tended to decrease with time during the nip-opening process. This is consistent with evaporative cooling.
3. At any given time during nip opening, sheet temperature decreases with increasing depth into the sheet. Hence, it is anticipated that flashing and venting would occur from the top surface of the sheet downward.

4. During nip opening, the internal sheet temperatures often went through a period where the temperature increased before following the general decreasing trend. This temperature increase will be shown, in the theoretical results section of this report, to occur while the system is still a subcooled liquid.

Theoretical Results

The thermodynamic model was used to program a computer model (V26/Master) to assist in the interpretation of the experimental results that are presented in this report. For ease of use and portability to a wide range of computers, the model was written in Microsoft ExcelVersion 5.0.

With the intention that future work would explore optimization of the decompression profiles, the computer model was written such that the decompression profile could be entered as a series of five points on the pressure-time curve. Hence, the present computer model assumes linear behavior between these points. As a consequence, some of the simulation results exhibit sudden changes of slope at these points.

Figure 30 shows the load decompression ramp profiles that were used to simulate the ramp experiments. For comparison with the measured load profiles, see Figure 6.
Figure 30. Nip-opening Load Depressurization Profiles as Used in the Thermodynamic Model.

Figures 31 through 36 show predicted temperature profiles for a number of the cases, for which there are experimental data for comparison. In each case, typical experimental internal sheettemperatures as measured at the beginning of the nip opening process were used as input to the computer model. Note that the predictions show the same general trends, with time, as the measured temperature profiles, see Figures 25 through 29 for comparison.

For both the experiments and the simulations, there is an initial period of time when the temperatures increase with time followed by a rapid drop in temperature. In the simulations, the time at which the temperature begins to drop corresponds to the instant of time when the system begins to evaporate (transitioning from a subcooled liquid to a saturated mixture). For the simulations the temperature profiles, occurring after the
transition, were only dependent on the assumed load decompression profile. For the experiments, the temperature profiles, occurring after the transition, were only dependent on the local pressure, through the vapor-pressure curve. Table 4 shows the experimental and simulated transition times for the ramp experiments.

Figure 31. Predicted Temperature as a Function of Time During Nip Opening Using Ramp NO, at a Set-point Temperature of 200 C.
Figure 32. Predicted Temperature as a Function of Time During Nip Opening Using Ramp NO, at a Set-point Temperature of 260 C.

Figure 33. Predicted Temperature as a Function of Time During Nip Opening Using Ramp C, at a Set-point Temperature of 200 C.
Figure 34. Predicted Temperature as a Function of Time During Nip Opening Using Ramp C, at a Set-point Temperature of 260 C.

Figure 35. Predicted Temperature as a Function of Time During Nip Opening Using Ramp A, at a Set-point Temperature of 200 C.
Figure 36. Predicted Temperature as a Function of Time During Nip Opening Using Ramp A, at a Set-point Temperature of 260 C.

Table 4. Experimental and Simulated Transition Times from Subcooled Liquid to Saturated Mixture for the Ramp Experiments.

<table>
<thead>
<tr>
<th>Case</th>
<th>Experimental Transition Time, sec.</th>
<th>Simulation Transition Time, sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>@ Location 1 @ Location 2</td>
<td>@ Location 1 @ Location 2</td>
</tr>
<tr>
<td>NO/200 C</td>
<td>0.009  &gt;0.019</td>
<td>0.006  &gt;0.020</td>
</tr>
<tr>
<td>NO/260 C</td>
<td>0.006  0.005</td>
<td>0.005  0.011</td>
</tr>
<tr>
<td>C/200 C</td>
<td>0.020  0.040</td>
<td>0.010  0.065</td>
</tr>
<tr>
<td>C/260 C</td>
<td>Not Available Not Available</td>
<td>0.010  0.035</td>
</tr>
<tr>
<td>A/200 C</td>
<td>0.025  0.060</td>
<td>0.013  &gt;0.013</td>
</tr>
<tr>
<td>A/260 C</td>
<td>~ 0.000  0.010</td>
<td>0.010  0.045</td>
</tr>
</tbody>
</table>

Figures 37 and 38 show, for two platen set-point temperatures, the predicted specific volume at various z-direction locations, defined by initial temperature, in the sheet as a function of time during nip opening. It is observed that while vaporization occurs more
rapidly for Ramp NO as compared to Ramp C and more rapidly for Ramp C than Ramp A, the predicted specific volume, when the sheet is exposed to the one atmosphere environment, was virtually independent of Ramp profile. Hence, at a platen set-point temperature of 200°C the specific volume of the system at the end of the ramp was approximately 0.17 m³/kg. Increasing the platen set-point temperature to 260°C resulted in a specific volume at the end of the ramp of about 0.21 m³/kg.

MODEL: Ts.p. = 200°C, Tp.s. = 184°C, T1' = 265°C

![Graph showing specific volume as a function of time during nip opening at a set-point temperature of 200°C.](image)

Figure 37. Predicted Specific Volume as a Function of Time During Nip Opening, at a Set-point Temperature of 200°C.
Figure 38. Predicted Specific Volume as a Function of Time During Nip Opening, at a Set-point Temperature of 260 C.

Figures 39 and 40 show the cumulative work done on the surroundings of the pores as a function of time during the nip-opening process. Here again, the work done by the time the sheet is in contact with the one atmosphere environment was independent of the particular Ramp profile.
Figure 39. Predicted Work Done on the Surroundings as a Function of Time During Nip
Opening, at a Set-point Temperature of 200 C.

Figure 40. Predicted Work Done on the Surroundings as a Function of Time During Nip
Opening, at a Set-point Temperature of 260 C.
As sheets impulse dried using the Ramp \textit{NO} profile delaminated and those using the Ramp \textit{A} profile did not delaminate, we conclude that, in these cases, end point system specific volume and work done do not account for the differences in sheet integrity.

Figures 41 and 42 show the rate of doing work on the surroundings plotted as a function of time during the nip-opening process. Here, it is graphically shown that the Ramp \textit{NO} case is significantly different in that it results in much higher rates of doing work on the surroundings. Hence, one mechanism that may explain the elimination of delamination for the longer ramps is that the power of the flashing event has been reduced. An alternate hypothesis may be that there is more time for venting of the flashed vapor when the decompression ramp is lengthened.

![Graph showing rates of doing work](image)

**MODEL**: $T_{s.p.} = 200 \, ^\circ C$, $T_{p.s.}=184 \, ^\circ C$, $T_1'= 165 \, ^\circ C$

Figure 41. Predicted Rate of Doing Work as a Function of Time During Nip Opening, at a Set-point Temperature of 200 C.
Figure 42. Predicted Rate of Doing Work as a Function of Time During Nip Opening, at a Set-point Temperature of 260 C.

**Interpretation Of The Internal Sheet Temperature Data:**

Referring to the experimentally determined internal sheet temperatures shown in Figures 25 through 29, and the experimental transition times reported in Table 4, we have identified regions of the experimental temperature profiles as being at saturation conditions. Hence, these temperature measurements can be used as a measure of the local internal sheet pressure. This is done by calculating these local pressures as the saturation pressures corresponding to the measured temperatures. This calculation has been done for each of the experiments as shown in Figures 43 through 47. Also shown in the figures, for comparison, are the corresponding load decompression profiles.

It is observed that the local internal pressures track well with the load decompression profiles, justifying to some extent the assumption made in the thermodynamic model. In addition, it is observed that the pressure at the top surface of the sheet always exceeds the load pressure. This is interpreted as implying that there is a substantial pressure drop from
the top surface of the sheet to the platen surface. Such a pressure drop can be provided by the flow of vented vapor from the sheet.

The mean pressure in the top one third of the sheet can be estimated as, \((P1+P2)/2\). From this estimate we may test the hypothesis that a sufficient imbalance of internal and external pressures, as the sheet comes in contact with the one atmosphere external environment, caused delamination. In Table 5, a mean pressure difference at the end of the ramp was calculated as, \({\left[(P1+P2)/2\right]-101}\). While the data is sparse, it does support the hypothesis that the long ramp prevents delamination by reducing the imbalance between internal sheet pressure and ambient pressure at the end of the ramp. Further experiments along these lines are needed to fully understand this delamination mechanism.

<table>
<thead>
<tr>
<th>Case</th>
<th>P1 at End of Ramp, KPa (absolute)</th>
<th>P2 at End of Ramp, KPa (absolute)</th>
<th>Mean Pressure Difference, kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/200 C</td>
<td>210</td>
<td>100</td>
<td>59</td>
</tr>
<tr>
<td>A/200 C</td>
<td>150</td>
<td>100</td>
<td>24</td>
</tr>
<tr>
<td>NO/260 C</td>
<td>700</td>
<td>300</td>
<td>399</td>
</tr>
<tr>
<td>A/260 C</td>
<td>700</td>
<td>150</td>
<td>324</td>
</tr>
</tbody>
</table>
Figure 43. Sheet Pressure as Deduced from Measured Temperature at Location 1 of the Sheet as a Function of Time During Nip Opening.
Figure 44. Sheet Pressure as Deduced from Measured Temperatures at Location 1 and 2 in the Sheet as a Function of Time During Nip Opening.
Figure 45. Sheet Pressure as Deduced from Measured Temperatures at Location 1 and 2 in the Sheet as a Function of Time During Nip Opening.
Figure 46. Sheet Pressure as Deduced from Measured Temperatures at Location 1 and 2 in the Sheet as a Function of Time During Nip Opening.
GOALS FOR FY: 1996 - 1997

1. Obtain temperature profiles and heat flux data at similar conditions as the earlier Krause experiments. Use these results, and the thermodynamic model, to investigate the mechanism by which HAPID eliminates sheet delamination. This is ongoing M.S. Thesis work that is expected to be completed by May 1996.

2. Develop a better fundamental understanding of internal and external heat transfer, vapor venting, and sheet expansion during nip opening. Incorporate these into an improved thermodynamics model that would be able to predict temperature and pressure as a function of time and z-direction location in the sheet, from known
load depressurization profiles, impulse drying conditions, and sheet structure. This work will be completed by September 1996.

3. Use the improved thermodynamic model and strategic experiments to determine guidelines for optimizing practical load decompression profiles for various grades, furnishes, and basis weights. This work will be completed by March 1997.

BIBLIOGRAPHY OF RELATED WORK


Thermodynamic Properties of Water:

The saturation pressure may be calculated from a polynomial fit to the vapor-pressure curve as shown in Figure A1. The fit is of the form,

\[ P_{\text{sat}} = A_0 + A_1 T + A_2 T^2 + A_3 T^3 + A_4 T^4 + A_5 T^5 \]

Where

\[
\begin{align*}
A_0 &= -0.63226 \times 10^3 \\
A_1 &= +0.17485 \times 10^2 \\
A_2 &= -0.17738 \times 10^0 \\
A_3 &= +0.83772 \times 10^3 \\
A_4 &= -0.10565 \times 10^5 \\
A_5 &= +0.24156 \times 10^8
\end{align*}
\]
If the temperature of the system is less than the saturation temperature at the system pressure, the system is a subcooled liquid. Knowing the temperature and pressure of the subcooled liquid, the specific volume of the system may be calculated from the following fit to standard steam table data.

\[ v = B_0 + B_1 P \]

Where

\[ B_0 = B_{00} + B_{01} T + B_{02} T^2 + B_{03} T^3 + B_{04} T^4 + B_{05} T^5 \]

\[ B_1 = B_{10} + B_{11} T + B_{12} T^2 + B_{13} T^3 + B_{14} T^4 + B_{15} T^5 \]

And where
\[ B_{00} = -0.15983 \times 10^{-2} \]
\[ B_{01} = +0.74136 \times 10^{-4} \]
\[ B_{02} = -0.80677 \times 10^{-6} \]
\[ B_{03} = +0.42693 \times 10^{-8} \]
\[ B_{04} = -0.10889 \times 10^{-10} \]
\[ B_{05} = +0.10835 \times 10^{-13} \]
\[ B_{10} = +0.97439 \times 10^{-7} \]
\[ B_{11} = -0.27882 \times 10^{-8} \]
\[ B_{12} = +0.30502 \times 10^{-10} \]
\[ B_{13} = -0.16068 \times 10^{-12} \]
\[ B_{14} = +0.40869 \times 10^{-15} \]
\[ B_{15} = -0.40406 \times 10^{-18} \]

Figure A2. Specific Volume of Subcooled Liquid Water vs. Pressure.
In a similar way, a number of other useful thermodynamic properties may be fit to known values of temperature and pressure

\[
\left( \frac{\partial \nu}{\partial T} \right)_p = K_0 + K_1 P
\]

Where

\[
K_0 = K_{00} + K_{01} T + K_{02} T^2 + K_{03} T^3 + K_{04} T^4 + K_{05} T^5
\]

\[
K_1 = K_{10} + K_{11} T + K_{12} T^2 + K_{13} T^3 + K_{14} T^4 + K_{15} T^5
\]

And where

\[
K_{00} = -0.55832 \times 10^{-4} \quad K_{10} = +0.22797 \times 10^{-8}
\]

\[
K_{01} = +0.18905 \times 10^{-5} \quad K_{11} = -0.76594 \times 10^{-10}
\]

\[
K_{02} = -0.23520 \times 10^{-7} \quad K_{12} = +0.95389 \times 10^{-12}
\]

\[
K_{03} = +0.13783 \times 10^{-9} \quad K_{13} = -0.55775 \times 10^{-14}
\]

\[
K_{04} = -0.38317 \times 10^{-12} \quad K_{14} = +0.15463 \times 10^{-16}
\]

\[
K_{05} = +0.40859 \times 10^{-15} \quad K_{15} = -0.16415 \times 10^{-19}
\]
Figure A3. Partial Derivative of Specific Volume With Respect to Temperature at Constant Pressure for Subcooled Liquid Water.

\[
\left( \frac{\partial u}{\partial T} \right)_p = L_0 + L_1 P
\]

Where

\[
L_0 = L_{00} + L_{01} T + L_{02} T^2 + L_{03} T^3 + L_{04} T^4 + L_{05} T^5
\]

\[
L_1 = L_{10} + L_{11} T + L_{12} T^2 + L_{13} T^3 + L_{14} T^4 + L_{15} T^5
\]
And where

\[
\begin{align*}
L_{00} &= +0.35476 \times 10^{10} \\
L_{01} &= +0.56697 \times 10^{-1} \\
L_{02} &= -0.12380 \times 10^{-2} \\
L_{03} &= +0.10572 \times 10^{-4} \\
L_{04} &= -0.38364 \times 10^{-7} \\
L_{05} &= +0.50299 \times 10^{-10} \\
L_{10} &= +0.22474 \times 10^{4} \\
L_{11} &= -0.22683 \times 10^{5} \\
L_{12} &= +0.49379 \times 10^{7} \\
L_{13} &= -0.41838 \times 10^{9} \\
L_{14} &= +0.15120 \times 10^{11} \\
L_{15} &= -0.19669 \times 10^{14}
\end{align*}
\]

Figure A4. Partial Derivative of Internal Energy With Respect to Temperature at Constant Pressure of Subcooled Liquid Water.
\[ P \left( \frac{\partial v}{\partial P} \right)_T = M_0 + M_1 P \]

Where

\[ M_0 = M_{00} + M_{01} T + M_{02} T^2 + M_{03} T^3 + M_{04} T^4 + M_{05} T^5 \]

\[ M_1 = M_{10} + M_{11} T + M_{12} T^2 + M_{13} T^3 + M_{14} T^4 + M_{15} T^5 \]

And where

\begin{align*}
M_{00} &= + 0.13391 \times 10^{-4} & M_{10} &= - 0.99147 \times 10^{-9} \\
M_{01} &= - 0.25254 \times 10^{-5} & M_{11} &= + 0.99013 \times 10^{-10} \\
M_{02} &= + 0.67126 \times 10^{-7} & M_{12} &= - 0.25830 \times 10^{-11} \\
M_{03} &= - 0.62526 \times 10^{-9} & M_{13} &= + 0.23694 \times 10^{-13} \\
M_{04} &= + 0.23865 \times 10^{-11} & M_{14} &= - 0.89488 \times 10^{-16} \\
M_{05} &= - 0.31977 \times 10^{-14} & M_{15} &= + 0.11799 \times 10^{-18}
\end{align*}
Figure A5. Pressure Times the Partial Derivative of Specific Volume With Respect to Pressure at Constant Temperature of Subcooled Liquid Water.

\[
\left( \frac{\partial u}{\partial P} \right)_{T} = O_0 + O_1 P
\]

Where

\[
O_0 = O_{00} + O_{01} T + O_{02} T^2 + O_{03} T^3 + O_{04} T^4 + O_{05} T^5
\]

\[
O_1 = O_{10} + O_{11} T + O_{12} T^2 + O_{13} T^3 + O_{14} T^4 + O_{15} T^5
\]
And where

\begin{align*}
O_{00} &= +0.17729 \times 10^1 \\
O_{01} &= -0.66677 \times 10^{-3} \\
O_{02} &= +0.90507 \times 10^{-5} \\
O_{03} &= -0.56876 \times 10^{-7} \\
O_{04} &= +0.16693 \times 10^{-9} \\
O_{05} &= -0.18586 \times 10^{-12}
\end{align*}

\begin{align*}
O_{10} &= -0.76408 \times 10^{-6} \\
O_{11} &= +0.28508 \times 10^{-7} \\
O_{12} &= -0.38671 \times 10^{-9} \\
O_{13} &= +0.24178 \times 10^{-11} \\
O_{14} &= -0.70567 \times 10^{-14} \\
O_{15} &= +0.77951 \times 10^{-17}
\end{align*}

Figure A6. Partial Derivative of Internal Energy With Respect to Pressure at Constant Temperature of Subcooled Liquid Water.
When the system temperature is equal to the saturation temperature corresponding to the
system pressure, the system is saturated. As such, the system temperature becomes a
dependent variable of system pressure. Thermodynamic properties are then a function of
either the saturation temperature or the saturation pressure and the quality of the system. A
number of useful thermodynamic relationships are given here as polynomial fits to
saturation temperature.

\[ \frac{du_{fs}}{dP} = D_0 + D_1 T + D_2 T^2 + D_3 T^3 + D_4 T^4 + D_5 T^5 \]

Where

\[ D_0 = -0.87516 \times 10^{+1} \]
\[ D_1 = +0.16725 \times 10^{+0} \]
\[ D_2 = -0.13213 \times 10^{-2} \]
\[ D_3 = +0.52728 \times 10^{+5} \]
\[ D_4 = -0.10521 \times 10^{+7} \]
\[ D_5 = +0.83497 \times 10^{-11} \]
Figure A7. Derivative of Internal Energy of Vaporization With Respect to Pressure as a Function of Temperature for Saturated Water.

\[ \nu_{\beta} = E_0 + E_1 T + E_2 T^2 + E_3 T^3 + E_4 T^4 + E_5 T^5 \]

Where

\[ E_0 = +0.18447 \times 10^2 \]
\[ E_1 = -0.36479 \times 10^0 \]
\[ E_2 = +0.29248 \times 10^2 \]
\[ E_3 = -0.11727 \times 10^4 \]
\[ E_4 = +0.23347 \times 10^7 \]
\[ E_5 = -0.18394 \times 10^{10} \]
Figure A8. Specific Volume of Vaporization as a Function of Temperature for Saturated Water.

\[ u_{jg} = F_0 + F_1 T + F_2 T^2 + F_3 T^3 + F_4 T^4 + F_5 T^5 \]

Where

\[ F_0 = +0.27306 \times 10^{+4} \]
\[ F_1 = -0.12981 \times 10^{-2} \]
\[ F_2 = +0.11254 \times 10^{+0} \]
\[ F_3 = -0.60891 \times 10^{-3} \]
\[ F_4 = +0.15622 \times 10^{-5} \]
\[ F_5 = -0.16241 \times 10^{-8} \]
Figure A9. Internal Energy of Vaporization as a Function of Temperature for Saturated Water.

\[ P \frac{d\gamma_{fs}}{dP} = G_0 + G_1 T + G_2 T^2 + G_3 T^3 + G_4 T^4 + G_5 T^5 \]

Where

\[ G_0 = -0.17620 \times 10^{-2} \]
\[ G_1 = +0.35298 \times 10^{0} \]
\[ G_2 = -0.28773 \times 10^{-2} \]
\[ G_3 = +0.11764 \times 10^{4} \]
\[ G_4 = -0.23949 \times 10^{-7} \]
\[ G_5 = +0.19341 \times 10^{-10} \]
Figure A10. Pressure Time the Derivative of Specific Volume of Vaporization With Respect to Pressure as a Function of Temperature for Saturated Water.

\[ P \frac{d\nu_f}{dP} = H_0 + H_1 T + H_2 T^2 + H_3 T^3 + H_4 T^4 + H_5 T^5 \]

Where

\[ H_0 = -0.12099 \times 10^2 \]
\[ H_1 = +0.35045 \times 10^4 \]
\[ H_2 = -0.38992 \times 10^6 \]
\[ H_3 = +0.21243 \times 10^8 \]
\[ H_4 = -0.56300 \times 10^{-11} \]
\[ H_5 = +0.58952 \times 10^{-14} \]
Figure A11. Pressure Times the Derivative of Specific Volume of Saturated Liquid Water With Respect to Pressure as a Function of Temperature.

\[ \frac{d\mu_f}{dP} = I_0 + I_1 T + I_2 T^2 + I_3 T^3 + I_4 T^4 + I_5 T^5 \]

Where

\begin{align*}
I_0 & = +0.10935 \times 10^2 \\
I_1 & = -0.20197 \times 10^0 \\
I_2 & = +0.15402 \times 10^2 \\
I_3 & = -0.59474 \times 10^5 \\
I_4 & = +0.11519 \times 10^7 \\
I_5 & = -0.89017 \times 10^{-11}
\end{align*}
Figure A12. Derivative of Internal Energy of Saturated Liquid Water With Respect to Pressure as a Function of Temperature.