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An Investigation of Factors Affecting Steambox Heating Effectiveness

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ABSTRACT
The work presented documents the third set of experiments conducted at IPST on factors affecting steambox heating effectiveness. The first set of experiments was directed at validating the usefulness of a new and unique piece of experimental equipment, the Steambox Comparator. The second set of experiments indicated that the wet sheet air permeability was a potential determinant factor in steambox heating efficiency. However, this second set of experiments was not designed to examine wet sheet air permeability. There was a fair amount of scatter in the data and only two fiber types were used. These shortcomings left some doubt as to the validity of the conclusion and were the motivation for the third set of experiments. The hypothesis was based on the concept that the sheet structure (pore shape, size, interconnectedness, fiber physical structure, etc.) is the primary factor governing steam penetration into the sheet. Permeability is an indirect characterization of the sheet structure, and sheet structure is affected by furnish, refining, pressing, and other sheet processing methods.

Sheets made from four different fiber types at two refining levels and three basis weights were used for this study. The primary conclusion from the experimental work was that air permeability of the wet sheet was a determinant factor in steambox heating efficiency and that furnish, refining, and basis weight are not determinant factors in controlling the effectiveness of steam heating. Furnish, refining, and basis weight are only important in that changing furnish or basis weight can alter the permeability of the sheet.

1. INTRODUCTION

Previous research into the factors controlling the heating effectiveness of steamboxes is limited. Much of the work covers machine trials in which the impact of the steambox on machine productivity was of primary interest rather than the mechanisms by which the heating occurred. A considerable portion of the work lacks sufficient information to draw anything but the most general conclusions. There are several notable exceptions. In addition to the work by Wahlstrom [1,2], two other researchers, Hodges [3] and Batty [4], produced some interesting work based on machine trials with fine paper, linerboard, and newsprint. One researcher who produced data on a laboratory scale was Woo [5]. Woo performed a study on the impact of vacuum on steam heating. In the study, roughly one half the steam was required to heat the web to 90°C when a vacuum box was used as compared to no vacuum. Woo also stated that there was a threshold vacuum level above which there was diminishing return. These results have some bearing on the work presented in this paper. A summary of previous steambox research is given by Patterson [6].

IPST has conducted three sets of experiments investigating steambox heating effectiveness [7]. The first set of experiments was directed at validating the usefulness of a new and unique piece of experimental equipment, the Steambox Comparator [8]. The second set of experiments was designed to examine the effects of basis weight, solids content, refining level, fiber type, and vacuum level. It was found that all these factors interact to determine the steambox heating effectiveness. In examining the data and the interactions, it was hypothesized that the examined factors alter a more basic property of the sheet and that the more basic property was the one that controlled the sheets' response to steam heating. As a result, a new hypothesis was developed, i.e., the air permeability of the wet sheet is the primary factor controlling the steambox heating effectiveness. As an initial test of the new hypothesis, sheets were fabricated using the identical pulp and procedures used to fabricate the sheets in the earlier experiments. The air permeability of these sheets was measured at the same moisture contents used in the earlier experiment. The data were then combined with the earlier experimental data and a statistical analysis performed. The analysis indicated that air permeability was potentially a primary determinant of steam heating effectiveness.

Despite the apparent confirmation of the hypothesis about the importance of wet sheet air permeability there were several problems. First, the original experiment was not designed to examine wet sheet air permeability. While every effort was made to ensure that the sheets used to measure the air permeability were the same as those used in the steam heating experiment, the sheets were made at different times and there was no way to confirm that both sets of sheets were exactly the same. Also, there was a fair amount of scatter in the data. Finally, only two fiber types were used, a virgin kraft and an OCC. These shortcomings left some doubt as to the validity of the conclusion that air permeability of the wet sheet was the controlling factor for steam heating effectiveness. This was the motivation for the third set of experiments, which is the subject of this paper.

The hypothesis for the third set of experiments was:

> Steam penetration into the sheet and correspondingly steam heating of the sheet are primarily governed by the air permeability of the sheet.

This hypothesis is based on the concept that the sheet structure (pore shape, size, interconnectedness, fiber physical structure, etc.) is the primary factor governing steam penetration into the sheet. Permeability is an indirect characterization of the sheet structure. Sheet structure is affected by furnish, refining, pressing, and other sheet processing methods. The study compared sheets made from four different furnishes at two basis weights and two refining levels. The sheets were subjected to an identical steaming process using the Steambox Comparator apparatus [Patterson 1996]. Temperature measurements were taken during the testing and subsequently used to calculate the steam heating effectiveness. The primary conclusion from the experimental work is that furnish, basis weight, and refining are not determinant factors in controlling the effectiveness of steam heating. Furnish, basis weight, and refining are only important in that changing furnish, basis weight, or refining alters the permeability of the sheet.

2. PRESSING PERMEABILITY STUDY

2.1 Sheet Preparation and Testing

Evaluating the hypothesis about the effect of sheet permeability required that sheets made from various furnishes and having a wide range of wet sheet air permeabilities be tested. The sheets should be similar in all other respects. This required that a pressing and permeability evaluation be performed.

Four different fiber types were used for this study:

1. Southern pine, virgin kraft, wet pulp.
2. Northern pine, virgin kraft, dry lap.
3. CTMP, dry lap.
4. Bleached hardwood, dry lap.

Each fiber type was refined in a one pound Valley Beater, using standard procedures, to two different refining levels, ~600CSF and ~400CSF. Using each of the refined furnishes and a square handsheet, mold four sheets were made with the following basis weights: 80 gsm, 100 gsm, 120 gsm. The sheets measured 0.203 m x 0.203 m (8 in x 8 in). These sheets were couched off the handsheet mold, individually stored in plastic bags, and separated into two groups. One group was pressed at 689 kPa (100 psi) for 30 seconds using a hydraulic hand press. This brought the moisture content to approximately 30%. The other group was placed between blotters and dried to approximately 30%.

The 0.203 m x 0.203 m (8 in x 8 in) sheets were cut into quarters 0.102 m x 0.102 m (4 in x 4 in). The sheets were numbered to indicate which sheet they were cut from and where in the sheet they were cut. Three of the 0.102 m x 0.102 m (4 in x 4 in) sections from each larger sheet were set aside for later testing using the Steambox Comparator. Thus, six sheets of each type that would be used for the steaming tests and two sheets of each type that would be used for the permeability study.

Each of the 0.102 m x 0.102 m (4 in x 4 in) sheets designated for use in the permeability study was cut into quarters. One quarter from each 0.102 m x 0.102 m (4 in x 4 in) sheet was used to determine the exact basis weight. Using that basis weight, the solids content of the remaining quarters (a total of six sheets) was adjusted to exactly 30%.

The air permeability measurements were conducted in the following manner: 1. Measure caliper, 2. Weigh sample, 3. Measure air permeability, 4. Weigh sample. Standard Gurley porosimeter procedures were used for the air permeability testing. In most cases the volume of air used for the permeability test was 100 cm^3. In the case of the low permeability sheets the air volume used was $25m^3$. The moisture loss during the testing was minimal.

2.2 Results

The results of the permeability testing are shown in Figure 2.1. The figures show that the sheets had a wide range of permeabilities (~10^{-11} to ~10^{-17} m^2). This was the desired result.

A closer examination of the permeability results produced some interesting findings which are shown in Figure 2.2 through Figure 2.5. Figure 2.2 is a graph comparing the permeability of the hydraulically pressed sheet to those that were brought to 30% solids by light pressing between blotters. This graph shows that at high initial permeabilities, pressing has little effect on the resultant permeability, but that at low initial permeabilities pressing significantly reduces sheet permeability. In
Figure 2.3, it can be seen that initial caliper has only a small effect on caliper changes produced by pressing. Caliper was measured using a soft platen. Figure 2.4 and Figure 2.5 show the relationship between permeability and caliper/basis weight or apparent density. In both figures all points fall on the same curve, regardless of furnish, basis weight, or refining. Figure 2.4 uses a logarithmic scale for permeability and demonstrates that there is a threshold minimum caliper for the sheet preparation methods used. Figure 2.5 shows that a linear fit can be found by manipulating the permeability value.

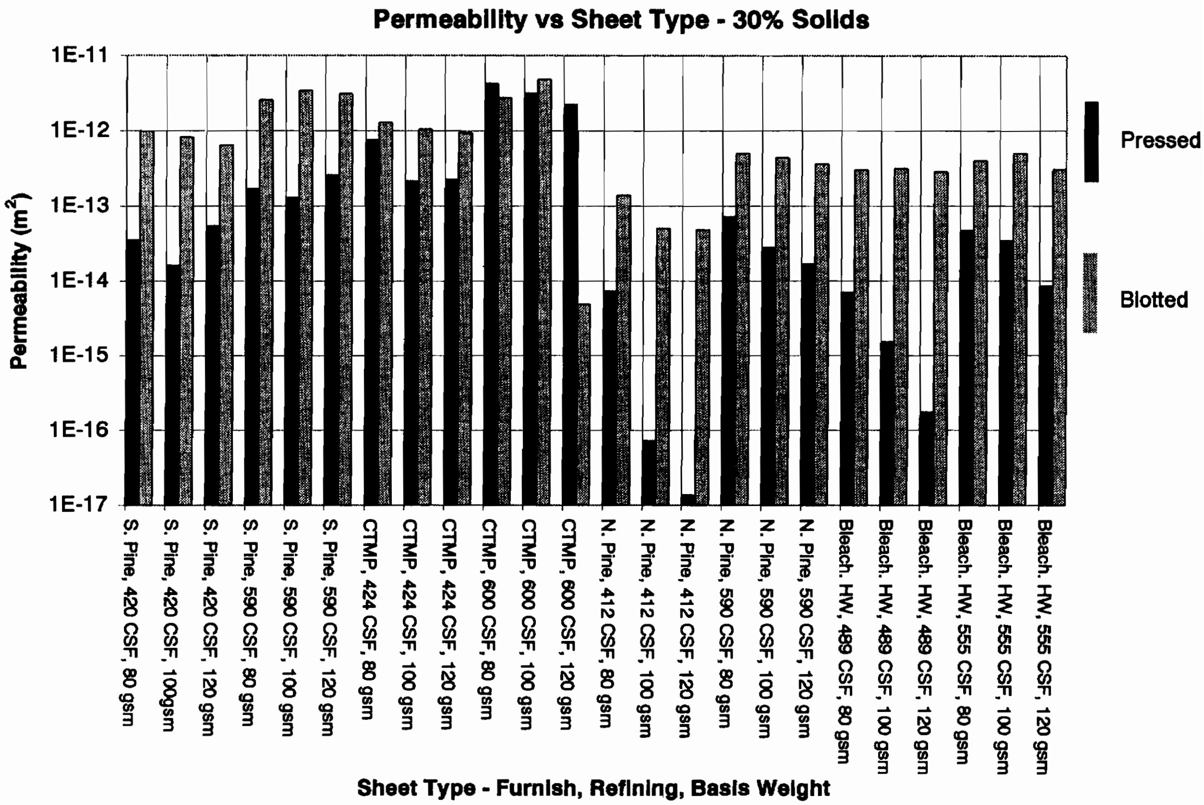

Figure 2.1 Air Permeability for Pressed and Blotted Sheets

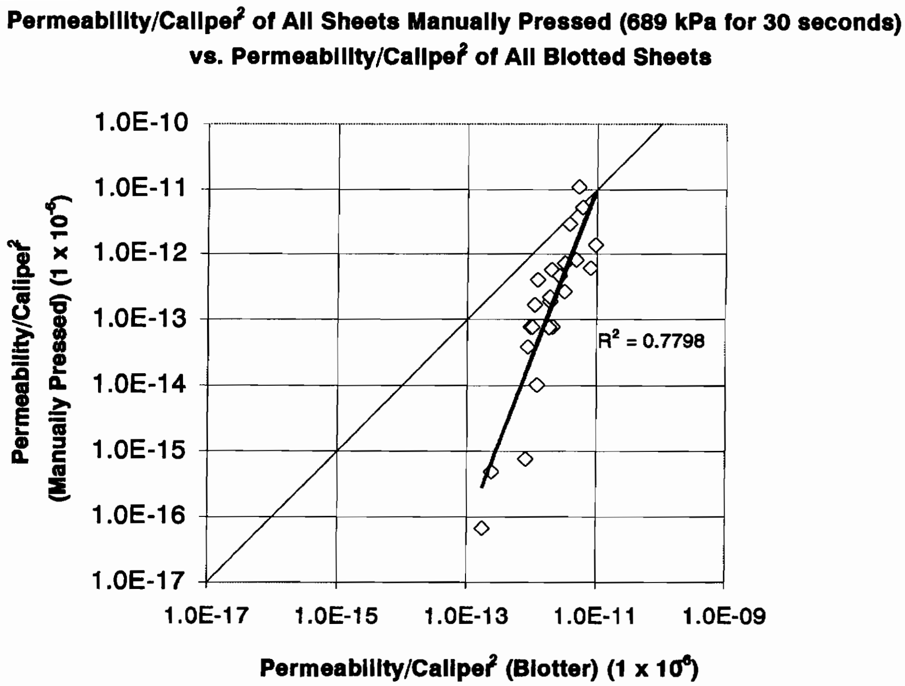

Figure 2.2 Permeability /Caliper² Manually Pressed vs. Blotted Sheets

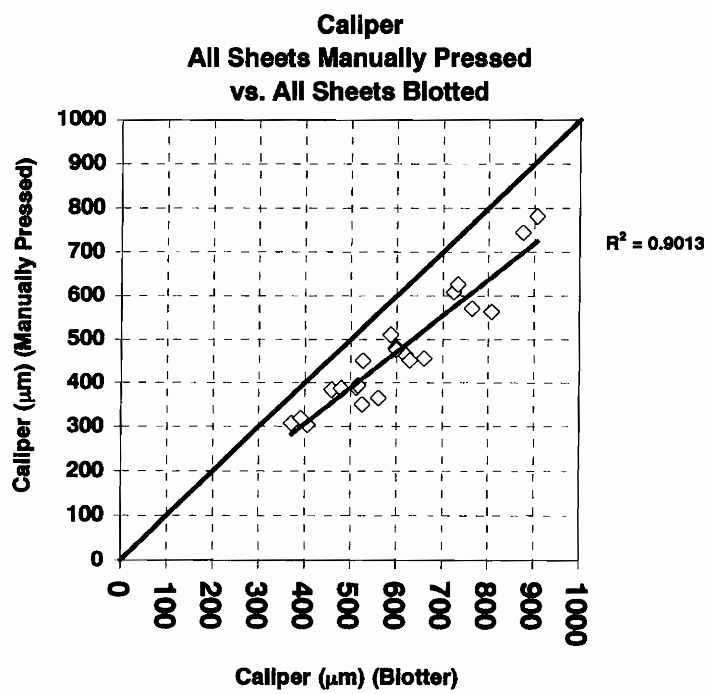

Figure 2.3 Caliper Manually Pressed Sheets vs. Caliper Blotted Sheets

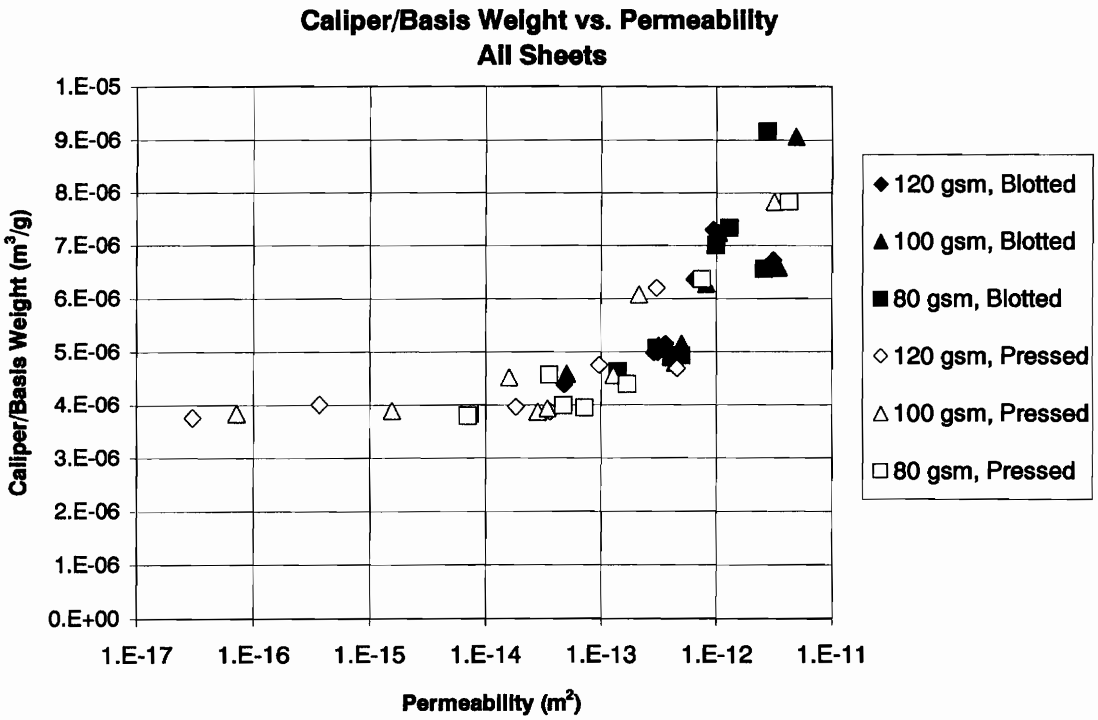

Figure 2.4 Caliper of All Sheets vs. Permeability

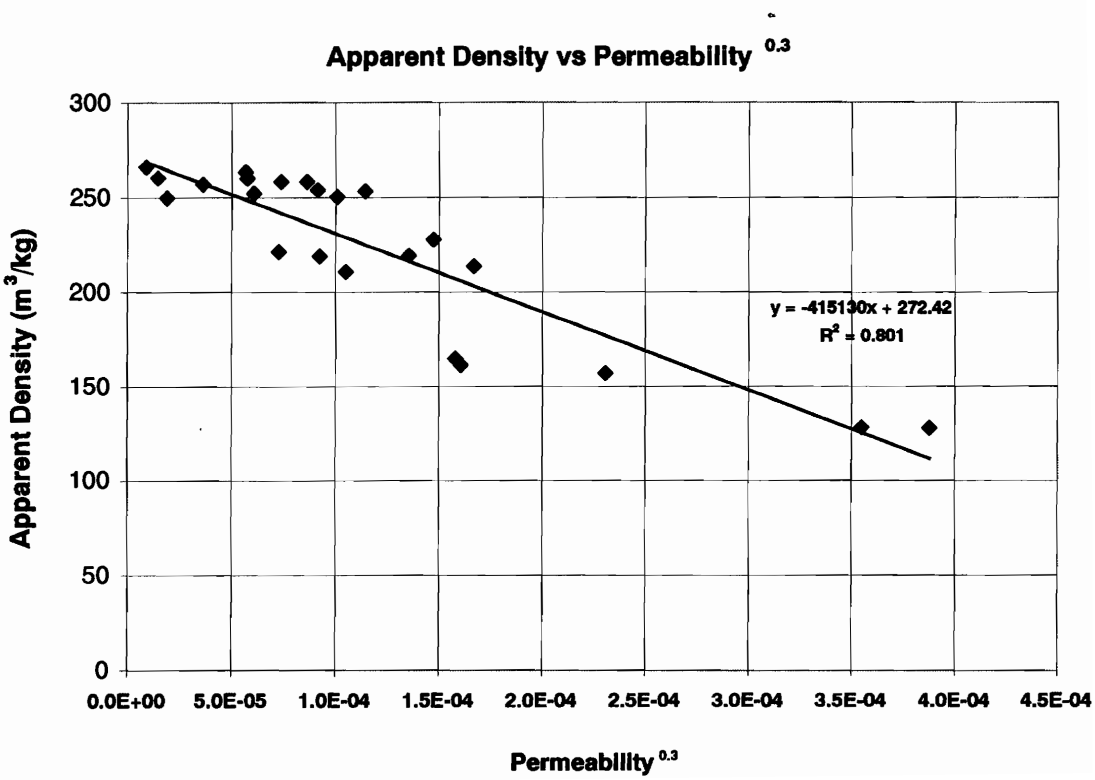

Figure 2.5 Apparent Density vs. Permeability

3. STEAM PENETRATION STUDY

3.1 Procedure

The Steambox Comparator was configured as in previous experiments [6]; the steambox and vacuum box were mounted approximately two-thirds of the way down the track. The vacuum box was of the same MD length as the steambox (0.30 m (12 in)) and was centered underneath the steambox. The operating parameters of the Steambox Comparator were held constant for all runs:

Steam Flow - 150 kg/hr
Steam Temp. (steambox exit) – 108°C
Steam Pressure (in steambox) – 103 kPa
Sled Speed – 305 m/min
Vacuum (in vacuum box) – 101 mm Hg
Data sampling rate – 1000 Hz

The relative placement of the sample, felt, and thermocouples is shown in Figure 3.1. Two thermocouples were sandwiched between the sample and the felt to record the temperature below the sample and therefore the extent of steam penetration, and two thermocouples were directly above the sample to record the surface temperature. The two thermocouples above the sample were held in place by being attached with string to a rigid plastic frame. The frame did not block steam flow to the top of the sample or vacuum to the bottom of the sample.

The samples used for the Steambox Comparator work were the three 0.102 m x 0.102 m (4 in x 4 in) sheets remaining from each of the original handsheets. These were brought to 30% solids based on their ideal basis weights of 80, 100, and 120 g/m^2. Each sample was then placed on a felt with a 16% moisture content. All samples were oven dried after testing to determine the exact consistency at the time of the run.

Single ply sheets were used to facilitate the testing. Using multiply sheets would have provided data on temperature profiles; however, this would have increased the time required for the testing at least five fold. The data produced by measuring the temperature on the bottom side of the sheet would be sufficient to test the hypothesis. Performing the test in a time efficient manner was critical given that there were 48 different sheet types and that there were six repetitions performed for each sheet type.

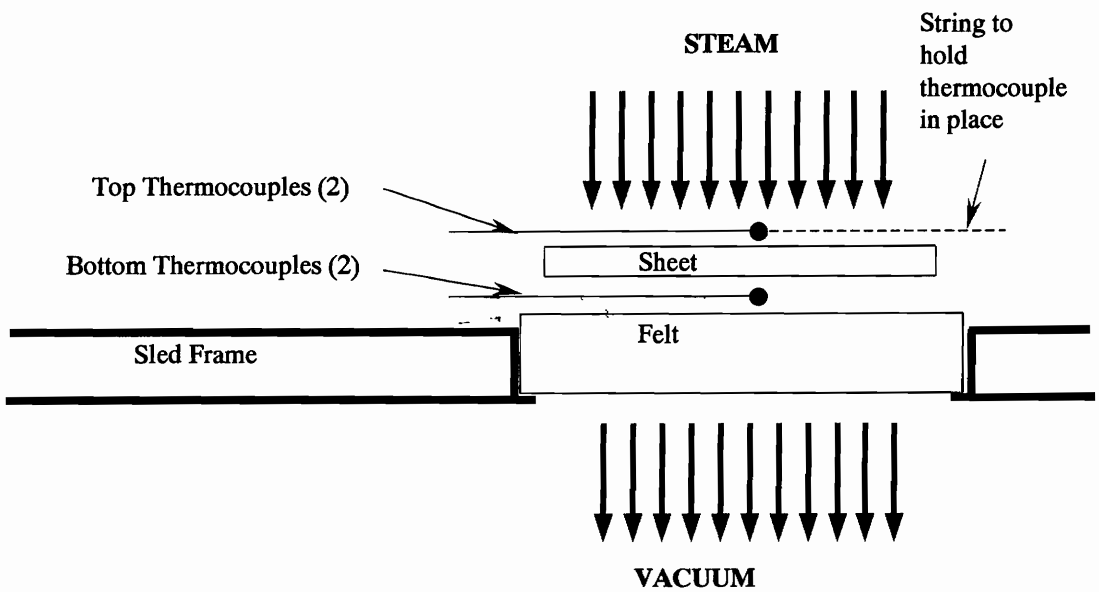

Figure 3.1 Sample Arrangement

3.2 Results

The data produced by each experimental run; thermocouple output, vacuum transducer output, photo eye output (speed), were downloaded into a spreadsheet for analysis. The thermocouple data in particular tended to have a lot of noise. At least one component of the noise was a 60 Hz signal, probably due to a building electrical supply. Prior to any further analysis, the thermocouple data were filtered to minimize the noise effect.

After filtering, the following process was implemented to treat the thermocouple data.
For each run:

1. Average the output of the two top thermocouples to give a top temperature with time.
2. Average the output of the two bottom thermocouples to give a bottom temperature with time.
3. Calculate sheet energy content based on the average thermocouple outputs.

For each sheet type (six repetitions):

1. Average the top temperature at 20 msec., 40 msec., and 55 msec.(steambox exit) after the sheet enters the steambox.
2. Average the bottom temperature at 20 msec., 40 msec., and 55 msec.(steambox exit) after the sheet enters the steambox.
3. Average the sheet energy content at 55 msec. after the sheet enters the steambox.

The most relevant information was the temperature at the bottom of the sheet. The exact temperature profile through the sheet was unknown; therefore, the energy absorbed was calculated assuming a linear temperature profile through the sheet. The thicker the sheet, the less valid was the assumption of a linear temperature profile and the more likely that total energy content was overestimated. The sheet energy content data were not highly accurate for the 100 gsm and 120 gsm sheets. The 80 gsm energy data appeared to be more accurate. Therefore, the temperature at the bottom of the sheet was used to evaluate the experimental results. Bottom surface temperature is plotted versus permeability/caliper^2 using a linear scale in Figure 4.1 and a logarithmic scale in Figure 4.2. In both cases, the results for all sheet types (furnish, refining, and basis weight) are shown. Permeability/caliper^2 is used because it is non dimensional and because of the earlier results that showed a relationship between permeability and caliper. As can be seen from both figures, a definite relationship exists between the bottom sheet temperature and permeability/caliper^2. Figure 4.2 is particularly interesting, because it indicates that for the conditions of the experiment there is a threshold permeability below which there is little or no penetration of steam into the sheet. This is the worst case scenario for the implementation of a steambox: all the steam condenses on the sheet surface. Using the experimental data it is possible to calculate the steam energy per unit area delivered to the sheet. Regardless total basis weight, it should be possible to use that number to calculate total sheet temperature rise.

In Figure 4.2 there are two additional lines labeled "theory". These lines are intended to show the possible location of the data points for alternative experimental conditions and are based on the following. The steam velocity into the sheet can be described using Darcy's Law

$$U = \Delta P/(\mu\ L/K)$$

Where U is steam velocity, ΔP is the pressure differential across the sheet, μ is steam viscosity, L is sheet caliper, and K is permeability. Setting $L_p = U\ t_{dwell}$, where L_p is the depth of steam penetration and t_{dwell} is the dwell time under the steambox, gives

$$L_p/L = \Delta P\ t_{dwell}/(\mu\ L^2/K)$$

or

$$L_p/L = (\Delta P\ t_{dwell}/\mu)(K/L^2)$$

The greatest possible value of L_p is L. When L_p = L, the steam has penetrated to the bottom side of the sheet, a condition that would yield considerable sheet heating. L_p/L can be thought of as a measure of the bottom sheet temperature or the y-axis of Figure 4.2. The terms in the first set of brackets on the right hand side of the equation can be thought of as operational parameters. The terms in the second set of brackets are plotted on the x-axis of

Figure 4.2 By the equation and by physical reasoning, L_p /L approaches a maximum of 1, when one or more of the following occurs:

1. ΔP increases
2. t_{dwell} increases
4. μ decreases

or

4. K increases
5. *L decreases*

Given these ideas and the experimental result it should be possible to make rough predictions of steambox heating effectiveness if the approximate sheet permeability and caliper and an anticipated location of a steambox are known.

4. CONCLUSIONS

The experimental results supported the hypothesis:

Steam penetration into the sheet and correspondingly steam heating of the sheet are primarily governed by the air permeability of the sheet.

This hypothesis is based on the concept that the sheet structure (pore shape, size, interconnectedness, fiber physical structure, etc.) is the primary factor governing steam penetration into the sheet. Permeability is an indirect characterization of the sheet structure. Sheet structure is affected by furnish, refining, pressing, and other sheet processing methods. Furnish, basis weight, and refining are only important in that changing furnish, basis weight, or refining alters the permeability of the sheet.

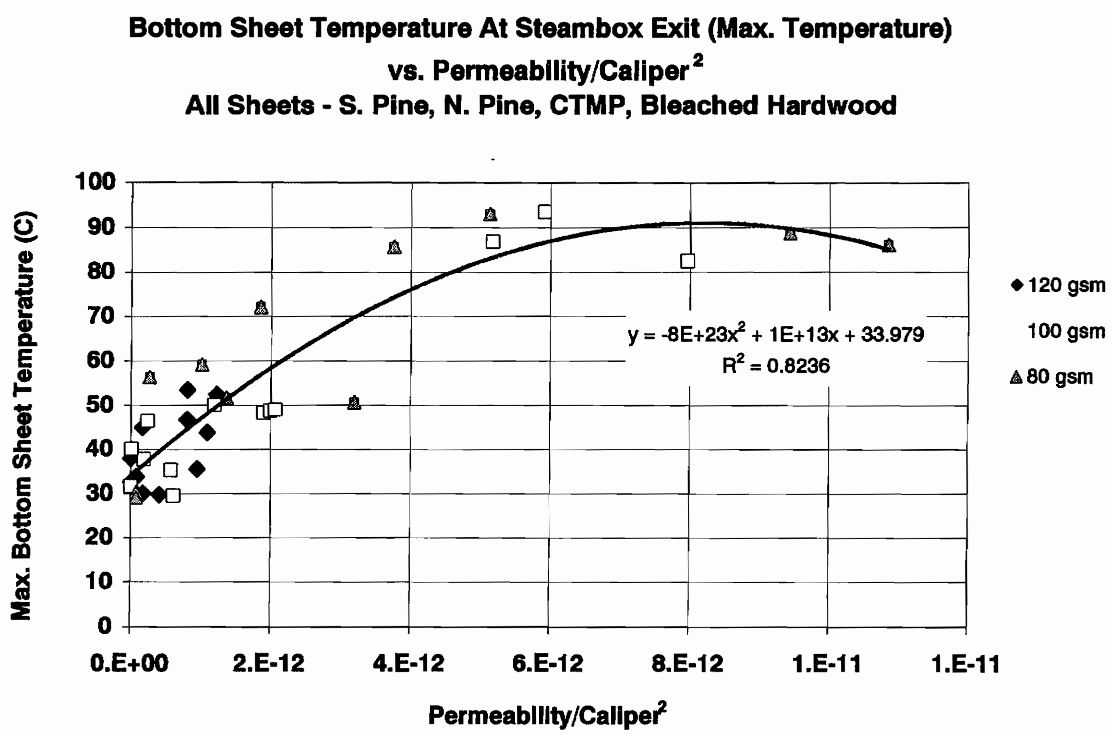

Figure 4.1 Bottom Sheet Temperature vs. Permeability/ Caliper²

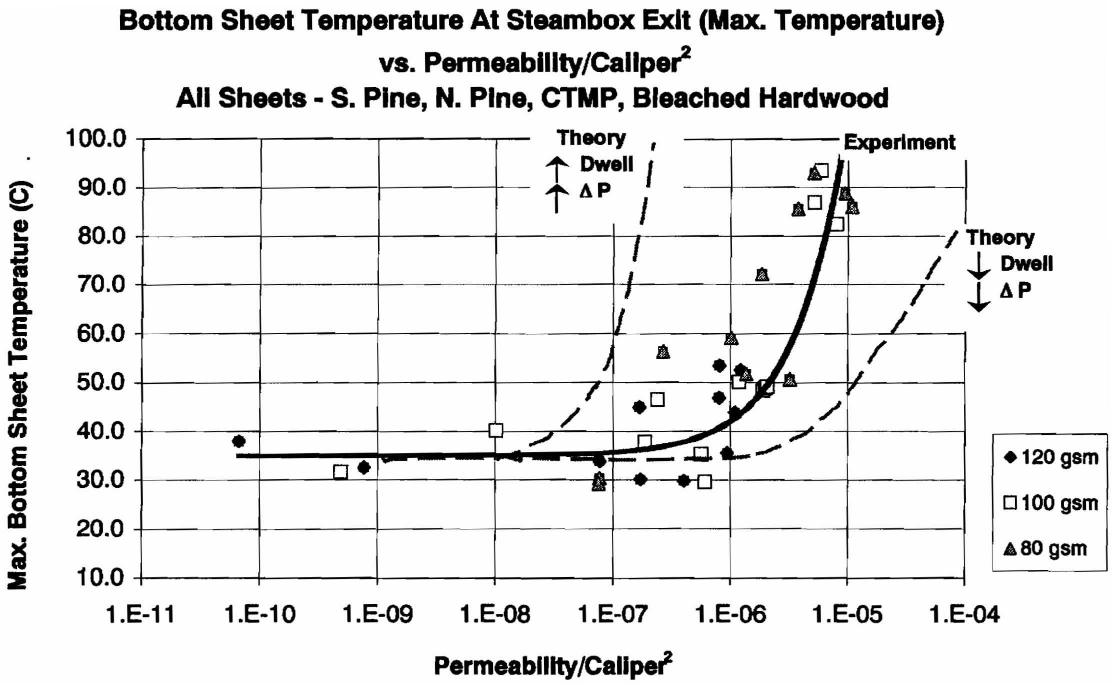

Figure 4.2 Bottom Temperature vs. Permeability/ Caliper²

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6. ACKOWLEDGMENTS

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