Steambox Comparator Experiments: Apparatus Validation and Investigation of Steambox Performance

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ABSTRACT

The Steambox Comparator, a unique apparatus for evaluating various web heating strategies, was constructed in 1994. This paper reports on series of experiments performed between 1995 and 1997. Initially, experiments were directed at validating the experimental setup. A follow on set of experiments investigated the effect of vacuum and sheet solids on steambox performance. The work showed that the Steambox Comparator was a potentially valuable experimental device. It also demonstrated the effectiveness of vacuum for enhancing web preheating (for the furnish examined) and the importance of steam penetration into the web for effective steam heating.

The final group of experiments surveyed the interaction of five parameters with the steam heating process. The major objectives of this half-fraction factorial experiment were to determine which parameters (furnish, basis weight, solids, refining, and vacuum) had the greatest effect on sheet temperature and energy absorbed, and to determine if there was a definable relationship between each parameter and the sheet temperature and/or energy absorbed. The results of these experiments showed sheet temperature to be a function of all 5 parameters, while energy absorbed was a function of 4 of 5 parameters, basis weight being the exception.

1. INTRODUCTION

The Steambox Comparator is a unique apparatus for evaluating various web heating strategies. Preliminary experiments were directed at demonstrating the capabilities of the system [1]. These preliminary experiments supported the common perception that vacuum and sheet solids effected steam heating, but also brought up two concerns regarding the experimental setup:

1. The effect of steam cross flow (in the CD direction) on the experimental results. Significant cross flow could produce a steam mass flow rate through the sample that was higher than the measured steam mass flow rate.
2. The effect of the layered sample construction on heating of the sheet.

The first part of this paper addresses those concerns. The conclusion of the work was that while the two issues are important there was not a significant effect in these experiments. Two groups of experiments were then run. The first group of experiments addressed the parameters of sheets solids and vacuum level. This work was motivated the desire to understand the mechanisms governing the effectiveness of steam heating. The second group of experiments addressed the parameters of sheet solids, sheet basis weight, sheet refining, sheet furnish, and vacuum level using a half-factorial experimental design. These experiments had the objective of determining which of the factors determined steambox effectiveness. These experiments are discussed in the final two sections of the paper.

2. FUNNELING – STEAM CROSS FLOW

The Steambox Comparator is a 9 m (30 ft) long track apparatus used for transporting an instrumented paper sample past a heating device, in this case a steambox (**Figure 1**). The sheet samples are typically multi-ply samples, that have a thermocouple embedded between each sheet layer. Each ply of the sample is a hand sheet that was formed at a pre-specified basis weight, removed from the forming screen without pressing, and die cut to the appropriate size. The sample is constructed by forming a “sandwich” of alternating sheet plies and thermocouples which is then pressed in a hand press to obtain the desired caliper and solids content. A plastic frame maintains the structural integrity of the sample (**Figure 2**). Moisture content is maintained by storing the sample in a plastic bag. The thermocouples used in all experiments were Type E, 0.05 mm (0.002 in) diameter, bare wire thermocouples. This basic configuration was used for all experiments reported on in this paper.

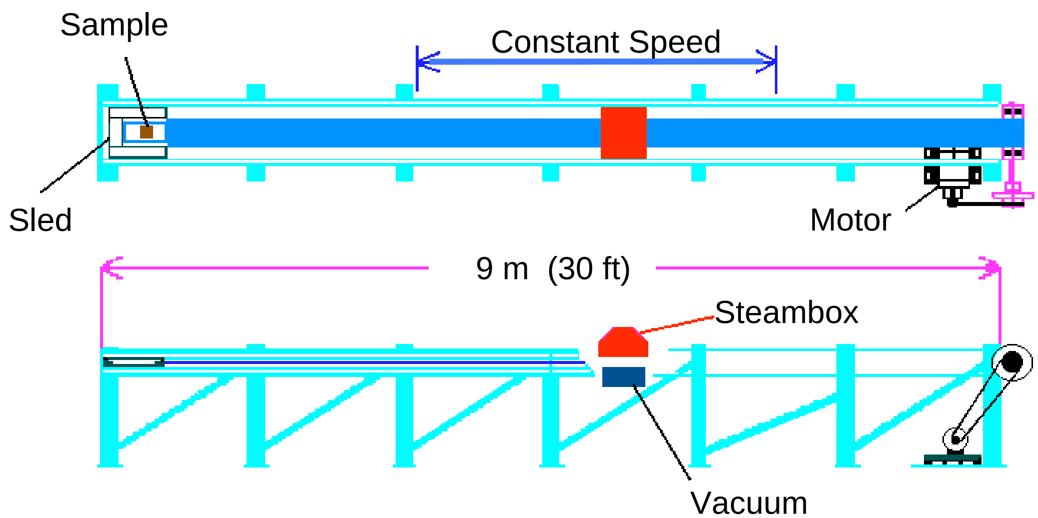

Figure 1. Steambox Comparator Apparatus.

The area around the sample is impermeable. Funneling potentially occurs when the applied vacuum is great enough that steam flows across the frame in the CD direction. Thus, the volume of steam pulled through the sample is greater than the volume of steam that existed directly above the sample. The result is an unrealistic steam supply to the sample. If funneling did occur, it would tend to exaggerate the effectiveness of the given steaming/sample setup. OCC pulp was prepared for these experiments. The pulp was beaten to approximately 615 ml CSF using a Valley Beater. Handsheets with a basis weight of 41 gsm were formed and die cut into 10.2 cm (4 in) diameter circles. The samples were constructed using five 41 gsm sheets, resulting in a 205 gsm sample. Previous experience had shown that this furnish was about "average" with respect to its amenability to steam heating.

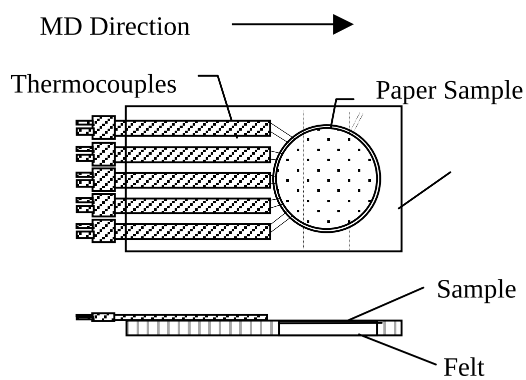

Figure 2. Sample and Plastic Frame.

The initial experimental set-up was as shown in **Figure 3**, the standard steambox/vacuum box setup that could potentially allow for funneling (Full-Width) and a setup that was intended to prevent funneling (Half-Width). The space between the steambox and vacuum box is greatly exaggerated in these figures. The steambox has two CD sections of equal width, 14.9 cm (5.875 in). Flow to the sections is controlled by manual valves. In the Full-Width configuration, the valves to both sections were completely open. In the initial Half-Width configuration, one valve was closed, while the other valve was completely open. In addition, some of the steam vents in the open portion were blocked. This reduced the CD width of the steambox to 10.2 cm (4 in). The only steam available to heat the sample was the steam directly above the sample. In both setups, the vacuum box was deckled so that vacuum was provided only to that area directly beneath the sample. A control was provided by running no vacuum cases for both setups. Analysis of the data showed that setup for the Half-Width configuration allowed air to contaminate the steam flow.

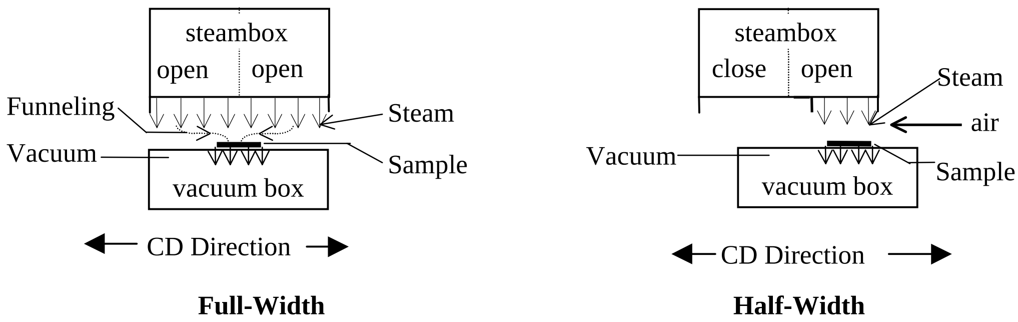

Figure 3. Initial Setup.

The configuration was changed to that shown in **Figure 4**. In the final Half-Width configuration two aluminum pieces were attached to the underside of the steambox. The purpose was to seal some of the vents in the open portion of the steambox and to fill the space adjacent to the steam vents, blocking air flow. As before the CD vent width was 10.2 cm (4 in). The Full-Width configuration remained unchanged. The height of the steam box above the sample was also reduced to 0.99 cm (0.390 in). The resultant system configuration produced consistent experimental data. The experimental conditions are summarized in **Table I**.

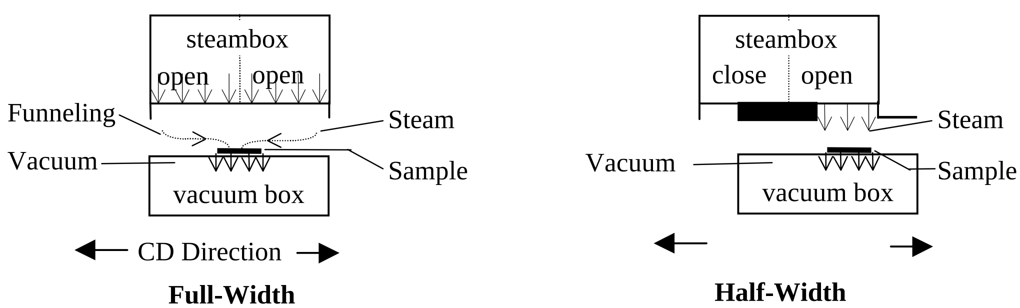

Figure 4. Final Configuration.

Table I. Average Experimental Conditions for Funneling Experimental.

	Full-Width Steambox		Half-Width Steambox	
Vacuum level (vacuum box)	0 mm Hg	190 mm Hg	0 mm Hg	190 mm Hg
Width of steambox	29.21 cm	29.21 cm	10.16 cm	10.16 cm
Mass flow rate of steam	210 kg/hr	210 kg/hr	74 kg/hr	74 kg/hr
Mass flow rate of steam/width	719 kg/hr m	719 kg/hr m	728 kg/hr m	728 kg/hr m
kg steam/kg paper	0.096	0.096	0.100	0.100
Steam temperature	113°C	113°C	113°C	111°C
Steam pressure	96.5 kPa	96.5 kPa	89.6 kPa	89.6 kPa
Sample speed	610 m/min	610 m/min	610 m/min	610 m/min
Samples Solids Content	35%	35%	35%	35%
Felt Moisture Content	16%	16%	16%	16%

Table II summarizes the results of the experiment. Steam Energy Available is the energy in the steam directly above the sample and is calculated based on the measured steam mass flow rate to the steambox. **Figure 5** and **Figure 6** present graphs of mass weighted temperature vs time and energy absorbed vs time. The mass weighted temperature is calculated by summing the weight of each layer multiplied by the average of the temperature on either side of the layer and dividing that sum by the total sheet mass. The absorbed energy is calculated using

$$E_{req'd} = \Sigma(m_f\, c_f + m_w\, c_w)[(T_{i+1} - T_i) - T_{initial}] \qquad (1)$$

where m_f = mass of fiber in layer (g), m_w = mass of water in layer (g), c_f = heat capacity of cellulose (1.33 J/g-°C), and c_w = heat capacity of water (4.19 J/g-°C). All data is the average of five separate experimental runs.

According to the hypothesis, funneling occurs only when vacuum is applied to the sample. Therefore, the two setups should yield similar results when vacuum is not used. This was the case. If funneling occurred in the full-vacuum cases, two things would be expected. The full-width setup would yield significantly higher sample temperatures than the half-width setup and the temperature rise in the full-width sample could require more energy than was available in the steam directly above the sample. Table II shows that the energy absorbed was similar in both the full- and half-width cases, and that the energy absorbed by the sample was never greater than the steam directly above the sample.

The primary conclusion was that funneling (steam CD cross flow) does not occur under the experimental conditions used. At lower freenesses, greater basis weights, and similar vacuum levels, it can reasonably be expected that there will also be no funneling. Although not specifically brought out in the presented data, air contamination of steam was shown to significantly reduce steaming efficiency.

Table II. Energy Comparison Funneling Experiment.

Test Condition	Steam Energy Avail. (kJ)	Maximum Average Sheet ΔTemp.	Energy for Max. Avg. Sheet Temperature	
			Energy Req'd(kJ)	% of Avail. Energy
Full Width, No Vacuum	0.439	11°C	0.201	45.8
Half Width, No Vacuum	0.458	10°C	0.214	46.7*
Full Width, Full Vacuum	0.439	23°C	0.392	89.3
Half Width, Full Vacuum	0.458	20°C	0.395	86.2*

*The initial Half-Width Configuration resulted in 33.0% of the available energy being used for the no vacuum case and 55.8% of the available energy being used for the vacuum case.

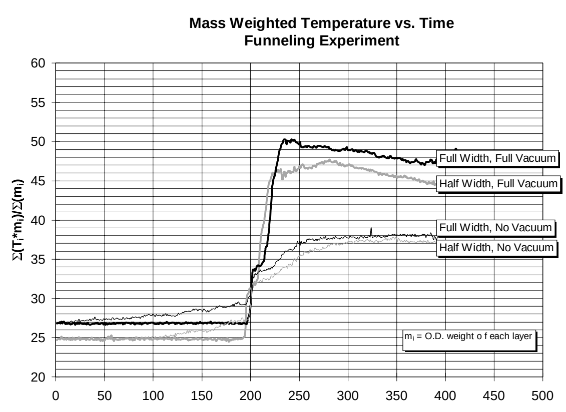

Figure 5. Funneling Experiment – Mass Weighted Temperature.

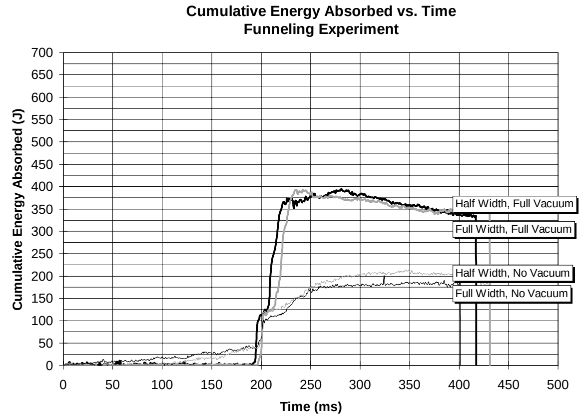

Figure 6. Funneling Experiment – Energy Absorbed .

3. SAMPLE LAYERING

There existed the possibility that the layers of the samples may affect the heating characteristics of the samples. When the steambox comparator was first constructed, a series of static (stationary) tests were conducted to determine if there was a difference between the heating of single-ply samples and multi-ply samples. There was no difference observed. No dynamic (moving sample) tests were conducted. In the intervening period, a number of observers have questioned the validity of using multi-ply samples.

Figure 7 shows the sample types compared and the vacuum conditions employed. The rationale was that if layering had an effect it would be more pronounced in the cases with the greatest number of layers. Because there was no method for embedding a thermocouple inside a single-ply sheet, a comparison of two-ply sheets with five-ply sheets was used. All samples had one thermocouple (represented by black ellipses) on the top surface, one thermocouple on the bottom surface, and at least one thermocouple at either 82 g or 123 g beneath the top surface. The funneling experiments described in Section 2 provided the data for the five-layer cases. All samples were made from the same furnish (OCC, 615 ml CSF). Data from the funneling tests showed that steam heating without vacuum produced only minor temperature increases at 123 g depth, therefore only vacuum cases were considered. The steambox setup and test conditions (steam flow rate, vacuum level, sample speed, samples solids, felt moisture) were the same as for the full-width funneling cases.

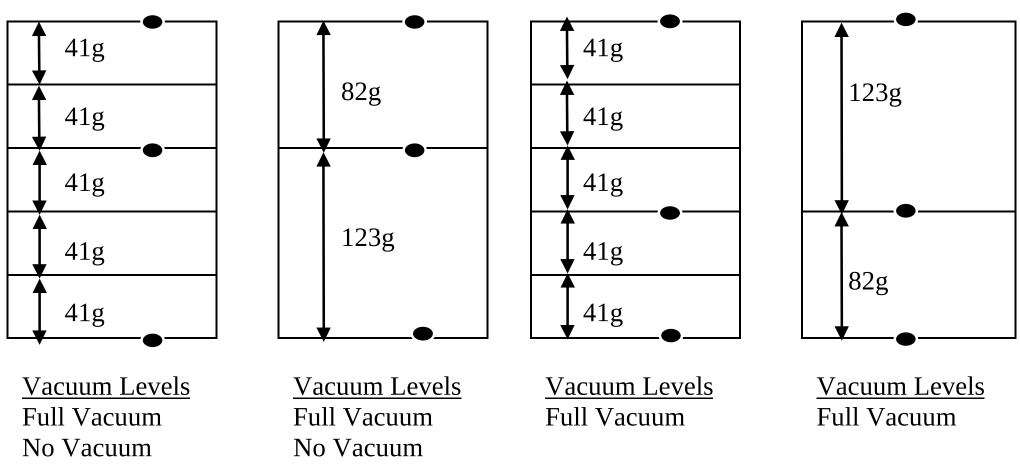

Figure 7. Dynamic Layering Investigation: Experimental Setup.

Table III summarizes the results. In the full-vacuum case at 82 g/m^2, Table III lists three entries for the five-layer sample, the first is the 'combined response' or the average of all runs taken together. The other entries are for a 'low temperature' and a 'high temperature' response. The 'low temperature response' was characterized by a temperature rise similar to the theoretical response of a semi-infinite plate subjected to a step increase in temperature at the exposed boundary, a conduction process. The temperature rise became significant as the sheet exited the steambox. All of the two-layer samples showed a response similar to this 'low temperature' response. The second type of response was the 'high temperature response', which had a rapid temperature rise while under the steambox. This behavior is more characteristic of a point closer to the top surface of the sheet and is indicative of condensation process.

Table III. Comparison of Average Temperature Response.

Sheet Depth	5-Layer Sample		2-Layer Sample	
	Average Temperature	Standard Deviation.	Average Temperature	Standard Deviation.
	Steambox Exit	Steambox Exit	Steambox Exit	Steambox Exit
82 g (no vacuum)	38°C	+/- 3°C	42°C	+/- 2°C
82 g (full vacuum)[1]	58°C	+/- 10°C	47°C	+/- 3°C
82 g (full vacuum)[2]	47°C	+/- 3°C	n/a	n/a
82 g (full vacuum)[3]	65°C	+/- 2.5°C	n/a	n/a
123 g (full vacuum)	41°C	+/- 6°C	34°C	+/- 4°C

1 – Combined temperature response, 2 – Low temperature response, 3 – High temperature response

In some test runs, both the 'low temperature' and 'high temperature' response were observed in the same sample at the same depth. It was concluded that the two responses were due to local sample differences and not differences between samples. Two possible explanations for these results are: the layers are thin enough that a significant portion of fines was lost during the forming process, thus giving a more permeable sheet, or there were local variations in sheet basis weight. A fiber analysis was performed on samples of four different basis weights (41, 82, 123, 205 gsm). There was little difference in fiber length. The percentage of fines was slightly less for the lighter weight sheets; however, the analysis showed that the variability within a sample was sometimes greater than the difference between samples.

The conclusion drawn from these results is that the different temperature responses were possibly caused by local sheet basis weight variations. The same variations are not seen deeper into the sheet because the greater sheet thickness produces an averaging of the sheet structural properties.

The experimental work showed that the layered samples can produce different results than non-layered samples, particularly in the vacuum case. These differences appear to be the result of local sheet structural variations. Experimentally, this can be taken into account by:

1. Running sufficient repetitions of each experimental condition to insure self-consistency in the data.
2. Using only layers which on visual inspection do show uniform formation.
3. Developing a layered sample pressing protocol which produces calipers, permeabilities, and solids contents that are similar to those produced by a single ply sample.
4. Quantifying the difference by running both types of samples.

4. SHEET SOLIDS AND VACUUM

It is generally held that vacuum can enhance steambox effectiveness and that webs at higher solids contents are more easily heated due to the lower water content [3]. However, there is little data in the literature that rigorously documents the effect of vacuum on steambox effectiveness [1, 2] or the interaction between vacuum and solids content. This set of experiments attempted to provide such data. The test matrix is shown in **Table IV**. The steambox setup and test conditions (furnish, refining level, sheet construction, steam flow rate, vacuum level, and sample speed) were the same as for the full-width funneling experiments.

Table IV. Experimental Matrix: Moisture & Vacuum.

	No Vacuum	76 mm Hg Vacuum	190 mm Hg Vacuum
25%	Completed	Completed	Completed
35%	Completed	-	Completed
45%	-	-	Completed

Figure 8 and **Figure 9** show the temperature responses for the 35% solids full vacuum (190 mm Hg) and no vacuum cases. In both cases, the sample enters the steambox at the time when the 0 gsm trace first shows a rapid increase. The slow increase in the no vacuum case between 0 and 200 ms is due to the steam billowing out in front of the steambox. The rise in internal sheet temperature after the sample exits the steambox is evident in both cases. In general the 25% solids samples showed slower and more delayed temperature rises inside the sheet. The 45% solids samples showed faster and less delayed temperature rises inside the sheet. The 76 mm Hg vacuum case showed results only slightly different from the no vacuum case. **Figure 10** and **Figure 11** show the mass weighted temperature response and energy absorbed for all samples. In these graphs, the sample enters the steambox at approximately 200 ms and exits approximately 30 ms later. The graphs show how there is little decrease in sheet average temperature or energy content for an extended period of time after exiting the steambox.

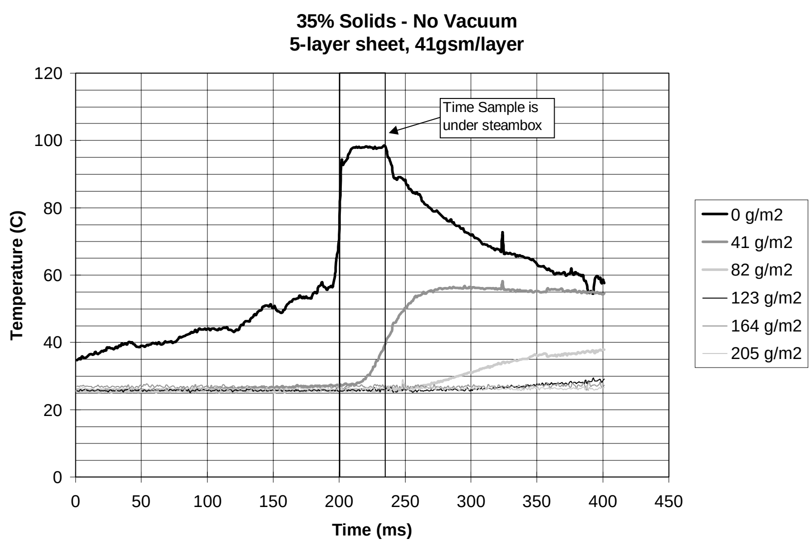

Figure 8. 35% Solids, No Vacuum, 5 layer – 205 gsm.

The following is a brief summary of the results:

1. As the solids level increases, the sample reaches a higher average temperature.
2. As the vacuum level increases, the sample reaches a higher average temperature.
3. As the vacuum level increases, the amount of energy transferred to the sample increases.
4. As the solids level decreases, the amount of energy transferred to the sample increases; a sample at 25% solids has more steam condense in it than a 45% solids sample, yet the 25% solids sample does not reach an equal temperature.
5. After passing the steambox, the total thermal energy in the sample remains relatively constant. The 25% solids, 178 mm Hg (7 in Hg) vacuum is a slight exception.
6. Once the sample has passed the steambox, the top of the sample cools, but the deeper layers warm up.

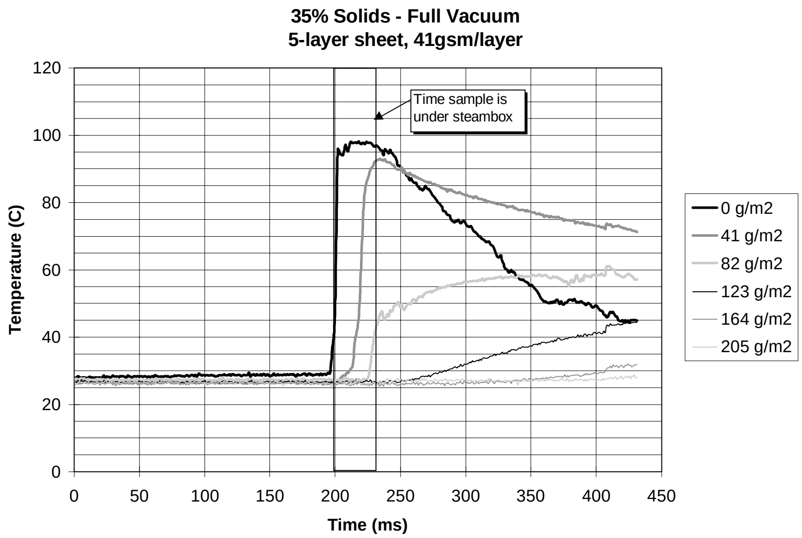

Figure 9. 35% Solids, Full Vacuum (190 mm Hg), 5 layer – 205 gsm.

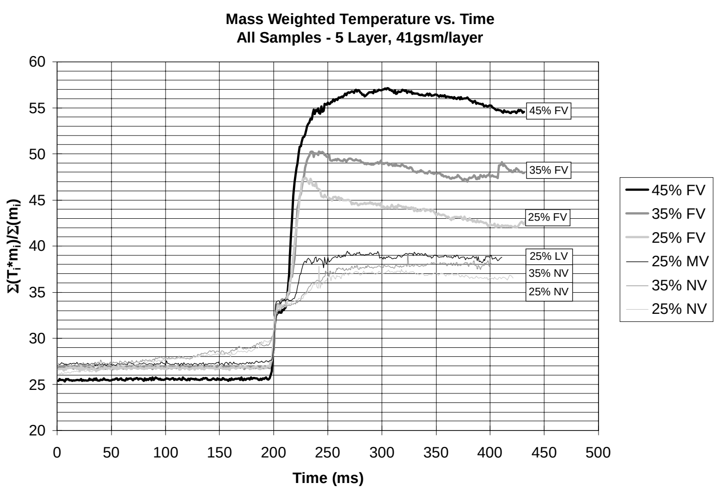

Figure 10. Mass Weighted Average Temperature Response All Cases.

Points 1 through 3 simply reconfirm commonly held beliefs about steam heating. The tendency of the lower solids sample to have more steam condense in it does not offset the addition energy requirement for raising the sample temperature an equal amount. One would expect that this would remain true regardless of other conditions as the condensation rate is largely dependent on the temperature difference between the condensing surface and the steam.

Points 5 and 6 suggest that convection heat loss, from the surface of high solids samples at temperatures at least as high as 60°C, is not significant in the time frames considered. At the speeds used, the time frame of 200 ms translates into a distance of 2 m (6.6 ft). The convection heat transfer appears to play a slightly larger roll in the case of the warmest 25% solids sample. Of equal significance is that if one were to observe only the surface temperatures of the sample, one would not have an accurate representation of either the average sheet temperature or the energy absorbed by the sample. This is because the majority of the heat transfer in the sheet after passing the steambox appears to be internal conduction toward the colder side. The total energy remains almost constant, but the top surface temperature drops, and the internal sheet temperatures gradually increase. This result contradicts the commonly held belief that convectional cooling from the top surface results in significant sheet energy losses. Convectional cooling is usually given as the motivation for placing a steambox as close as possible to the press.

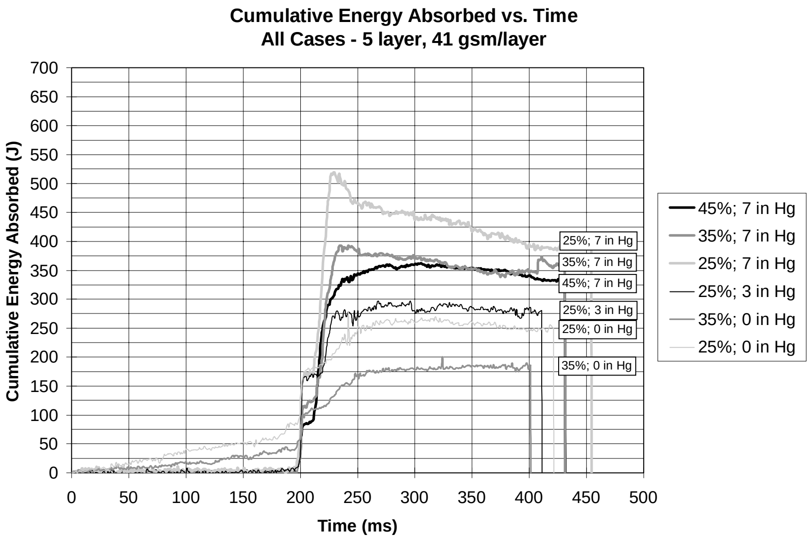

Figure 11. Cumulative Energy Absorbed – All Cases.

Figure 9 shows the average response of a five-layer sample at 35% solids when exposed to full vacuum. The thermocouple at the 82 g/m^2 position shows a sharp increase just as the sample exits the steambox. The temperature increases approximately 30°C in 10 ms. The question arises as to what process could cause this increase. The approximate amount of energy required to cause this temperature rise is calculated using eq. 1, which yields an energy required of q = 223 J. Given the time period, the heat transfer rate is 22.3 J/s. A conduction heat transfer coefficient of k = 29.7 W/(m°C) is required to transfer the same amount of energy in the given time. This is of the same order of magnitude as the thermal conductivity of lead (33 W/m°C). In the case of convection Cansler [4] gives the figure of h =~2 kW/(m^2°C) as a rough estimate of the convection heat transfer coefficient for steam heating of a sintered steel plate. This convection heat transfer coefficient allows the transfer of only 6 J in the given time.

Using a formulation for condensation inside an array of tubes given by J.P. Holman [5], an approximation of the condensation contribution can be found. This particular formulation is for low Reynolds numbers, which is appropriate for this case. The pertinent equation is

$$h_{bar} = 0.555\{[\rho_{liquid}^2\ g\ k^3\ h_{fg}]/[\mu\ d\ (T_g - T_w)]\}^{1/4}$$

where

ρ_{liquid} - density of water, 960 kg/m^3
g - acceleration due to gravity, 9.8 m/s^2
k - conductance of water at 100°C, 0.68 W/m°C
h_{fg} - heat of condensation, 2.257x10^6 J
μ - viscosity of water at 100°C, 2.82x10^{-4} Pa s

d - diameter of tubes (pores) assumed to be 1/20th of sheet thickness, 0.001/20 m
T_g - Temperature of steam, 100°C
T_w - Temperature of web, 35°C

$$h_{bar} = 28540 \text{ W/m°C}.$$

The heat transfer per unit area is

$$q_{area} = h_{bar}\ \Delta T = (28540 \text{ W/m}^2\text{°C})(100-35) = 1855 \text{kW/m}^2.$$

Using q_{area} and h_{fg} to find the required steam mass transfer rate per unit area, and using the result to calculate the mass of steam condensed in the sample, the theoretical heat transfer is,

$$q = m_{condense}\ h_{fg} = (0.0822 \text{ g})(2257 \text{J/g}) = 185 \text{ J}.$$

This is 20% less than the actual value. Given the approximations made, the agreement is good and confirms that the recorded temperature rise was mostly due to condensation. The factor that makes this assumption possible is the short time duration. This assumption is not valid once the sample has exited the steambox as the time scale is considerably different.

These calculations demonstrate that it is reasonable to assume that while the sample is under the steambox only condensation makes a significant contribution to the temperature changes in the sheet. This assumption, along with the experimental data, makes possible a calculation of the amount of steam that has condensed in each layer of the sheet. **Figure 12** presents a graph steam condensation per layer for the various cases tested. A predominant factor in determining steam penetration and condensation appears to be the vacuum level. Sheet solids has a lesser effect. The relatively small difference between the no vacuum and 76 mm Hg (3 in Hg) vacuum and the large difference between the 76 mm Hg (3 in Hg) vacuum and the 190 mm Hg (7 in Hg) vacuum case indicate that the effect of vacuum may be nonlinear.

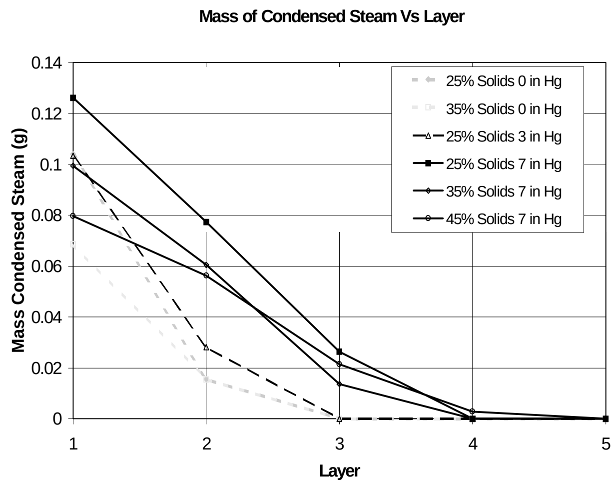

Figure 12. Mass Condensed Steam vs. Layer.

While many of the results presented here tend to only reconfirm widely held beliefs, there are several findings of interest.

1. The total energy content of the sheet does not significantly change for an extended period of time after exiting the steambox. Therefore, convectional cooling off the exposed surface is not a significant energy loss.
2. The primary mechanism for heating the sheet while it is under the steambox is condensation. Conduction and convection do not act fast enough to contribute significantly.
3. Steam does penetrate into the sheet and the deeper the penetration the greater the heating of the sheet. When steam condenses only on the surface, sheet heating is minimal.

5. HALF-FACTORIAL STUDY

No previous investigations of steamboxes have attempted to determine which sheet characteristics control the effectiveness of steam heating. If one or two specific sheet characteristics could be identified as the primary characteristics controlling sheet heating, then the applicability of steam heating to a specific situation could be determined by simply evaluating those characteristics. This experiment was a half factorial experiment that examined five parameters at two levels (See **Table V**).

Three (123 gsm) and five (205 gsm) layer samples of virgin kraft and OCC pulp were prepared in a manner similar to that specified in Section 2. Each layer was 41 gsm, but was die cut into a 0.10 m x 0.10 m (4 in x 4 in) square instead of a circle. Temperature through the thickness of the sheet was measured as the samples were propelled underneath a steambox at paper machine speeds 610 m/min (2000 fpm) using the Steambox Comparator.

The temperature of the sheet was quantified by the mass-weighted temperature, but is referred to simply as *temperature*. The energy absorbed by the sheet was calculated directly from the thermocouple data and the moisture content of the sheet using eq. 1. The maximum temperature and energy absorbed for each experimental case are shown in Table V.

Table V. Maximum Temperature and Energy Absorbed.

Case Number	Solids	Furnish	Refining (CSF)	Basis Weight (gsm)	Vacuum	Temp. (^oC)	Energy (J)
1	25%	OCC	400	123	On	42	254
2	45%	OCC	400	123	Off	59	263
3	25%	Virgin Kraft	400	123	Off	47	340
4	45%	Virgin Kraft	400	123	On	76	411
5	25%	OCC	600	123	Off	34	246
6	45%	OCC	600	123	On	83	449
7	25%	Virgin Kraft	600	123	On	93	860
8	45%	Virgin Kraft	600	123	Off	50	216
9	25%	OCC	400	205	Off	34	270
10	45%	OCC	400	205	On	44	270
11	25%	Virgin Kraft	400	205	On	45	730
12	45%	Virgin Kraft	400	205	Off	43	270
13	25%	OCC	600	205	On	30	381
14	45%	OCC	600	205	Off	42	245
15	25%	Virgin Kraft	600	205	Off	37	370
16	45%	Virgin Kraft	600	205	On	68	609

5.1 Energy Analysis

Energy is the measurement of interest from a fundamental point of view. The temperature is determined by the amount of steam energy absorbed by the sheet. Using standard statistical methods for factorial experiments [6] the main effects and interactions for energy absorbed were calculated and are shown graphically in **Figure 13**. The magnitudes of the effects and interactions are quantified in terms of energy absorbed (J). A t-distribution was chosen to represent the distribution of the random error with 95% error bounds. Using the differences between replicate runs for each case, the standard error was calculated as ±48J and is indicated by the vertical lines in Figure 13. The significant main effects and interactions were those which had magnitudes greater than the ±48J experimental error bound and are labeled in the Figure.

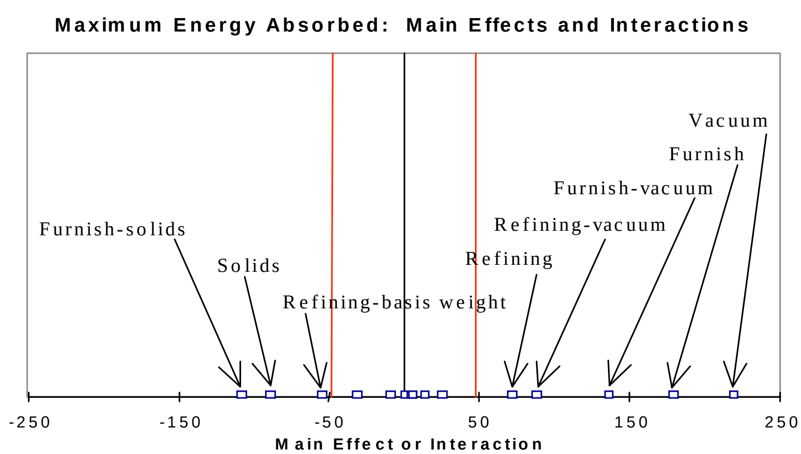

Figure 13. Main Effects and Interactions Affecting Energy Absorbed Quantified in (J).

There were significant interactions between the main parameters which required that all five parameters be examined in closer detail. A more detailed examination was also suggested by the unexpected independence of energy absorbed from basis weight. The interactions were assessed by examining subsets of the full matrix. The subsets were created by grouping cases using a common interaction parameter. Each subset had a factorial experimental design, allowing the same statistical techniques to be applied. A vacuum subset allowed assessment of the two vacuum interactions, while a furnish subset allowed assessment of the two furnish interactions. The main effect of the remaining interaction parameter (e.g., Refining, in the Refining-Vacuum evaluation) was calculated for the vacuum and furnish subsets and the results compared to evaluate the interaction. This was done using an analysis of reduced factorial matrices.

The two significant interactions involving vacuum were assessed by removing vacuum as a parameter. The runs were divided into two groups, one containing only cases when the vacuum is on, and one containing only cases when the vacuum is off. The different effect of each parameter can be seen by comparing these two groups **(Table VI)**. Examination of the table shows that any parameter has less of an effect when the vacuum is off than when the vacuum is on.

Table VI. Relevant Main Effects and Interactions by Vacuum.

Main Effect or Interaction	Vacuum Off	Vacuum On
Average	277J	496J
Furnish	43	314
Solids-Furnish	-54	-163
Solids	-58	-121
Refining	-16	158
Basis Weight	23	4

The magnitude of the main effects and interactions reveals that in the Vacuum-Off case, only the solids main effect and the solids-furnish interaction significantly affect the amount of energy absorbed by the sheet. Furnish has a potentially marginal effect. An interesting point is that the changes produced by refining do not have a significant effect. In the Vacuum-On cases, furnish and refining become additional significant effects. Note that the effect of basis weight is negligible for both cases, the same as was found for the full matrix analysis. The Vacuum On cases are ones in which there was vapor flow into the sheet. The results potentially indicate that the structural changes induced by refining and changing furnish effect flow through the sheet and steam condensation.

The two significant interactions involving furnish can be assessed by removing furnish as a parameter. The results of the reduced factorial analysis are shown in **Table VII**.

Table VII. Relevant Main Effects and Interactions by Furnish.

Main Effect or Interaction	OCC	Virgin Kraft
Average	297J	476J
Vacuum	83	354
Solids	19	-198
Refining-Vacuum	87	88
Refining	66	76
Refining-Basis Weight	-23	-86
Basis Weight	-11	38

Each parameter had a significant interaction with another parameter in the full matrix analysis. In **Table VIII**, arrows are used to indicate significant parameter interactions. The vacuum effect is readily evident. This large dependence on vacuum, suggests that the controlling parameter for steambox effectiveness is related to vapor/air flow through the sheet. Such a parameter is wet sheet air permeability. An interaction worth noting is the Vacuum-Furnish interaction. This suggests that the increased effectiveness of steambox heating can be negated by sheet structural changes related to furnish changes. Because the interaction involves vacuum, this would indicate a structural change that influences flow through the sheet, giving further support to the concept of wet sheet air permeability. The solids content is also assumed to affect the permeability of the sheet, and thus affect the amount of energy absorbed. As the solids content increases, it is assumed that the void space increases due to the reduced amount of moisture in the inter-fiber spaces.

Table VIII. Energy Effects for Cases Revealing Interactions.

	Vacuum Off	Vacuum On	OCC	Virgin Kraft
Average	277J	496J	297J	476J
Vacuum (Off to On)	N/A	N/A	+83 ↔	+354
Furnish (OCC to Virgin Kraft)	+43	+314 ↔	N/A	N/A
Refining (400 CSF to 600 CSF)	-16	+158 ↔	+66	+76
Solids (25% to 45%)	-58	-121 ↔	+19 ↔	-198
Basis Weight (123 to 205 gsm)	+23	+4	-11	+38
Experimental Error (95%) = 48J				

The basis weight has no effect on the amount of energy absorbed for the basis weights considered (123 and 205 gsm). This implies that steam condenses in the same amounts at the same depths within a sheet independent of the sheet's basis weight. This conclusion, however, seems unlikely, and this result should be noted for future reference. If wet sheet air permeability is a determinant factor, then the basis weight difference may not have had a significant effect in this experiment.

The most significant observations on the energy absorbed are summarized below:

- In vacuum off cases, solids and furnish are controlling factors.
- In vacuum on cases, solids, furnish, and refining are controlling factors.
- Solids can increase or decrease the amount of energy absorbed due to two competing factors: rate of condensation and permeability.
- Basis weight appears to have a negligible effect, which is unexpected.

5.2 Temperature Analysis

The main effects and interactions for sheet temperature were calculated using the same methods as were employed for the energy calculations. The results are shown graphically in **Figure 14**, the significant main effects and interactions are labeled. A two-tailed t-distribution was examined with 95% probability of the random error being contained within the limits. The bound on the experimental error is ±7ºC. The experimental error bounds are represented by the vertical lines in Figure 14.

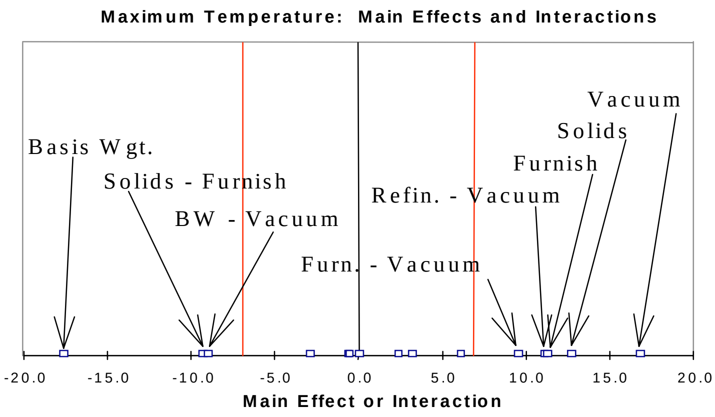

Figure 14. Main Effects and Interactions Affecting Sheet Temperature Quantified in °C.

A cursory review of the significant effects does not reveal anything unexpected. Sheets that are more easily heated are thinner and drier and have undergone less refining and recycling, and vacuum increases the temperature. As with the energy analysis, the parameter interactions require that all five parameters be examined in detail. Furnish appeared in two interactions (Solids-Furnish and Furnish-Vacuum). Vacuum interactions were also very significant (Refining-Vacuum, Furnish-Vacuum, and Basis Weight-Vacuum). A vacuum subset allowed assessment of the three vacuum interactions, while a furnish subset allowed assessment of the two furnish interactions. The main effect of the remaining interaction parameter (e.g. Refining, in the Refining-Vacuum evaluation) was calculated for both subsets and the results compared to evaluate the interaction.

The main effects and interactions for the vacuum off and vacuum on analyses are shown in **Table IX**. The effect that each parameter has can be seen by comparing the two columns. For instance, furnish has no effect on the sheet temperature when no vacuum is applied, while a virgin kraft sheet would be 20.8 ºC hotter than an OCC sheet on average when the vacuum is on. The analysis shows that there is always less of an effect of any parameter when the vacuum is off than when the vacuum is on. Note that refining has a strong effect on the sheet temperature in the vacuum on case, but the effect appeared negligible in the full matrix analysis.

Table IX. Relevant Main Effects and Interactions by Vacuum.

Main Effect or Interaction	Vacuum Off	Vacuum On
Average	43.4ºC	60.1ºC
Basis Weight	-8.7	-26.7
Solids	10.3	15.0
Furnish	1.7	20.8
Basis Weight-Refining	6.4	-12.3
Refining	-5.0	17.1

The Solids-Furnish and Furnish-Vacuum interaction can be assessed by removing furnish as a parameter. Solids had an unexpectedly negligible effect on the virgin kraft sample temperatures (**Table X**). Based on the earlier experimental results, an increase in solids should cause an increase in sheet temperature. Vacuum had a negligible effect on the OCC sheet temperatures, possibly indicating that the vacuum was unable to produce appreciable steam penetration into the sheet. This is an important result, since it implies that adding a vacuum box to a similar OCC case will be of no benefit.

Table X. Relevant Main Effects and Interactions by Furnish.

Main Effect or Interaction	OCC	Virgin Kraft
Average	46.1C	57.4C
Basis Weight	-17.1	-18.2
Vacuum	7.2	26.3
Solids	22.0	3.3
Refining-Vacuum	11.1	11.0
Basis Weight-Vacuum	-8.3	-9.7
Refining	2.9	9.2

Each of the studied parameters (furnish, refining, basis weight, solids, vacuum) had a significant interaction with another parameter in the full matrix analysis. An analysis of the effect of each parameter by case is given in **Table XI**. Arrows are used to indicate significant parameter interactions. Before this experiment, it was unclear which parameters would have the most effect on sheet temperature. This experiment has revealed that all five parameters have a significant effect on sheet temperature and are of the same order of magnitude (Table XI). Temperature has previously been shown to be a function of basis weight and solids, and this is verified by these experimental results, with one apparent exception: virgin kraft sheet temperatures are unaffected by solids content. This result is unexpected and needs to be examined further in the future.

The most significant observations on sheet temperature are summarized below:

- All five parameters can have a significant effect on sheet temperature.
- Basis weight is always significant.
- Solids is significant, except when offset by a reduction in energy absorbed.
- OCC and virgin kraft reach the same temperature when no vacuum is applied.
- Energy and temperature trends are similar, but not the same, because temperature is also dependent on basis weight and solids content.

One important conclusion is that a lack of vacuum will limit the sheet temperature to under 50ºC, even for the most conducive combinations of the investigated parameters. However, the application of vacuum may not increase the sheet temperature significantly. The sheet temperatures vary from an insignificant 30ºC to a very hot 93ºC when vacuum is applied. Therefore, the addition of a steambox and vacuum box will not always increase the sheet temperature significantly and might not produce any significant productivity gains.

Table XI. Temperature Effects for Cases Revealing Interactions.

	Vacuum Off	Vacuum On	OCC	Virgin Kraft
Average	43ºC	60ºC	46ºC	57ºC
Basis Weight (123 to 205gsm)	-8 ⟷	-27	-17	-18
Vacuum (Off to On)	N/A	N/A	+7 ⟷	+26
Solids (25% to 45%)	+10	+15	+22 ⟷	+3
Furnish (OCC to Virgin Kraft)	+2 ⟷	+21	N/A	N/A
Refining (400CSF to 600CSF)	-5 ⟷	+17	+3	+9
Experimental Error (95%) = 7ºC				

5.3 Summary

The major objectives of this half-fraction factorial experiment were to:

1. Determine which parameters (furnish, basis weight, solids, refining, and vacuum) have the greatest effect on sheet temperature and energy absorbed, and
2. Determine if there is a definable relationship between each parameter and the sheet temperature and/or energy absorbed.

The sheet temperature was shown to be a function of all five parameters, while energy absorbed was a function of four of five parameters (basis weight being the exception). There was no one relationship between any of the parameters and temperature and/or energy absorbed. In the no vacuum case, solids content was a significant, and possibly controlling, factor. However, there is some indication of sheet structure, either through refining or furnish, controlled energy absorbed. This experiment has shown that under certain conditions, a steambox will not significantly increase the sheet temperature.

The results of this study suggest, but do not confirm, that air permeability of the wet paper web may be the dominant parameter controlling the amount of energy absorbed and thus the process of steam heating a web. There is also some indication that the web specific surface may be a factor, particularly in predicting steambox performance without the use of vacuum. Additional experimental work is required to determine if this is the case and what interactions with solids occur.

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