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Dynamic Thickness and Temperature Measurements During Wet Pressing and Impulse Drying

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Abstract

This paper summarizes the results of dynamic sheet thickness and temperature measurements made while a sheet was undergoing wet pressing or impulse drying on an electrohydraulic platen press. The dynamic thickness measurement system was based on the impedance variation caused by eddy currents induced by thin copper perforated targets that were embedded in the sheet. Temperature profiles were measured by embedded thermocouples.

The main findings of the work are as follows:

- Impulse drying at elevated temperatures results in higher and nonuniform sheet compression as compared with wet pressing.
- Analysis of compression rate curves for both wet pressing and impulse drying indicate four compression intervals associated primarily with expression of air, expression of free water, expression of bound water, and rewet, respectively.
- The temperature profile in the sheet shows that a heat pipe process during prolonged decompression tends to even out the sheet temperature across the sheet and reduce the likelihood of sheet delamination.

Background

When designing the press section of a paper machine, machine builders intend to maximize water removal. Estimates indicate that the energy expenditure for removing water by drying is reduced by 4% for every 1% gain in dryness in the press section. Sheet temperature and water removal in the press section may be increased by preheating and/or by the use of impulse drying.

A significant factor impeding implementation of impulse drying of linerboard and other heavy grades is delamination. A number of solutions have been suggested to inhibit delamination (Orloff 1994, Orloff et al. 1997). The main thrust was to reduce the imbalance between internal vapor pressure in the sheet and applied pressure. These works suggested that this could be accomplished by either gradually decreasing the applied pressure at the end of the nip or by increasing the ambient pressure as the sheet is decompressed. As the internal vapor pressure is determined by sheet temperature, information that describes temperature and compression profiles in the nip is of interest.

Experimental procedures

The measurement system that was developed was used to investigate linerboard compression and expansion during conventional wet pressing and impulse drying using different pressure pulses. The work reported here improves upon that of Burton et al. (1986) and Burns et al. (1990) by simulating shoe press nips rather than roll press nips, and including a press felt in the nip rather than a rigid, porous water receiver.

A schematic of the press simulator is shown in Figure 1.

The temperature of the platen of the electrohydraulic press was set from ambient to 350°C using a temperature controller. The sheet with the felt and rigid plate was placed on the top of the sensor housing and subjected to a programmed press pulse. Five sensors were used for displacement measurements of the perforated copper targets (25 microns thickness), which were positioned at the different levels in the sheet. Three of the targets were embedded in the sheet and the other two targets were positioned on the top and bottom of the sheet. The results reported in this work were obtained with 205-gsm unbleached sheets with equidistant targets (five 41-gsm layers).

When impulse drying was simulated, two thermocouples were placed on the top and bottom of the sheet. Temperature profiles were measured by using thermocouples that were embedded into the sheet. The sheets were made from repulped linerboard that contained 30% OCC. The repulped linerboard had a freeness of 660 mL CSF.
Peak pressure was about 5100 kPa, nip time was about 40 ms, and press impulse was 0.12 MPa sec.

Results and discussion

Compression during wet pressing and impulse drying

Examples of the sheet compression profiles at ambient and elevated temperatures are shown in Figures 2 and 3. For the purposes of convenience, transverse positions of the targets, as functions of the nip time, are shown in normalized units as referenced to the ingoing thickness of the sheet. The dynamic thickness curves for both ambient and elevated temperatures provide evidence that the thickness minima occur toward the end of the nip. The figures further indicate that an increase in platen temperature results in:

- Higher compression of the sheet.
- Nonuniform densification of the impulse-dried sheet due to high compression of the top layer of the sheet.
- Lower sheet expansion during nip opening unless the sheet is delaminated.

The observed effects as to the impact of elevated platen temperature on the sheet compression in the nip support previous observations (Burton et al. 1986, MacGregor 1983, Cutshall and Hudspeth 1993).

Compression intervals in the nip

Based on the sheet thickness vs. nip time data, compression rate curves were calculated for the sheets pressed at different platen temperatures. An example of compression rate and applied pressure is shown in Figure 5 for pressing at room temperature. Analysis of compression rate curves for both wet pressing and impulse drying made it possible to identify four intervals in the nip:

- Interval 1 is from the entrance of the nip to the maximum of the compression rate curve. During this period of the nip, the compression rate in the nip is high. The applied pressure is thought to be primarily balanced by compressed air contained within the pores.
- Interval 2 is from the maximum of the compression rate curve to the instant when the compression rate drops to a value close to zero. During this interval, water from the larger pores is removed from the sheet.
- Interval 3 is from the point where the compression rate is close to zero (or a discontinuity in the slope of compression rate curve takes place) to zero slope of the compression curve in the nip. In this interval, water from the smaller pores (interfiber water) is removed from the sheet.
- Interval 4 is from zero in compression rate to the exit of the nip. In this interval, the sheet expands. The rate of sheet expansion varies and has an extreme magnitude at some point of the expansion phase of the nip.

Wahlstrom (1969) and Nilsson and Larsson (1968) have identified similar intervals in the press nip in their fundamental works for transversal flow nip of a roll press. Burton et al. (1986) also showed similar compression intervals based on an experimentally measured apparent density curve. Using the information derived from dynamic thickness measurements, the boundaries between the intervals and the acting mechanisms of water removal can be identified from the compression rate curve.

Under the assumption that in Interval 1 of the nip, compressibility of the sheet is mainly determined by compressibility of the air contained in the sheet, the compression rate can be calculated based on the equation of ideal gas for air at constant mass of air. By differentiating this equation with respect to time, the following expression for compression rate can be obtained:

$$-dL/dt = L_o \rho_{oa} \varepsilon_o R T_o^* (dP/dt)/P^2 = L_o \varepsilon_o P_o^* (dP/dt)/P^2,$$

Where

L_0, ρ_{0a}, ε_0 are thickness, air density, and air porosity of uncompressed sheet;
T_o is sheet temperature, K;
$R = 286.7$ J/(kg K) is gas constant for air;
$P_o = 101325$ Pa is atmospheric pressure.

It is important to note that absolute pressure must be used in the above formula. That is, atmospheric pressure should be added to the gauge pressure of the measured applied pressure curve.

The experimental and calculated compression rate curves are shown in Figure 5. There is a reasonable match between these two curves. The theory is useful in estimating the instant of time when the sheet becomes saturated and water removal from the sheet begins. Subsequently, water removal from the sheet is determined by the sheet compression rate.

Heat pipe process inhibits the likelihood of delamination in a decompressed hot sheet

Measurements of temperature profiles were conducted at platen temperatures of 100°C, 200°C, and 300°C. To demonstrate significant difference in temperature profiles, when the sheet is heated below and above the normal boiling point, the temperature profiles are shown in Figures 6 and 7 for platen temperatures of 100°C and 300°C, respectively.

Figure 6 shows that at a platen temperature of 100°C, sheet temperature in both the compression and the decompression phase of the nip is controlled by heat conduction and convection of expressed water. The change of sheet temperature in the nip occurs more or less monotonically.

The temperature profile changes significantly when the sheet temperature exceeds the normal boiling point, which happens in the decompression phase of the nip. Sheet temperature profiles at a platen temperature of 300°C (see Figure 7) indicate an intense heat transfer process, which involves vaporization and condensation within the decompressed sheet. Such a process is usually termed a heat pipe process.

Measured temperature profiles of the sheet subjected to pressing at platen temperatures of 300°C reveal that the decompression of the sheet is accompanied by evaporation and vapor flow from the upper hotter zone of the sheet toward the colder layer of the sheet, where condensation occurs.

The following phases of the heat pipe process are suggested, based on the measured temperature curves:

- Vaporization in the top heated part of the sheet and reduction of its temperature;
- Vapor flow from the top hotter part of the sheet to the bottom colder part of the sheet due to a gradient of internal vapor pressure;
- Condensation of vapor in the bottom part of the sheet and an increase of its temperature;
- A drop in internal pressure again triggers vaporization if the sheet temperature exceeds the saturation temperature, and the process is repeated again.

This process leads to rapid evening out of the temperature across the sheet. If during the decompression phase of the nip the maximum sheet temperature is brought down below 100°C, delamination should not take place. Otherwise, a balance between internal forces applied to the fiber network and the transversal wet strength of the sheet determines the likelihood of delamination.

The proper design of the decompression process is a key factor in inhibiting delamination. The time required to decompress the sheet without causing delamination can be estimated from simple physical considerations based on the known amount of heat to be removed from the hot top part of the sheet by the vaporization-condensation process. In that calculation, Darcy's law can be used to determine the vapor flow velocity.

Such an estimate yielded a required decompression time of about 9 ms. Orloff et al. (1998) reported that delamination occurred at a decompression time of 4 ms. At the next selected decompression time of 19 ms and higher, delamination was prevented.

Conclusions

Application of a dynamic thickness and temperature measurement system allowed the development of new insights concerning sheet compression and expansion during wet pressing and impulse drying.

The main findings are as follows:

- Major differences in the sheet compression profiles at elevated and conventional temperatures were found to exist.
- Compression intervals associated with expression of intrafiber and inter-fiber water out of the sheet were identified based on the sheet compression measurements and the estimated compression rate curve.
- Controlled sheet decompression at the end of the nip is a significant factor for inhibiting delamination at a high platen temperature.

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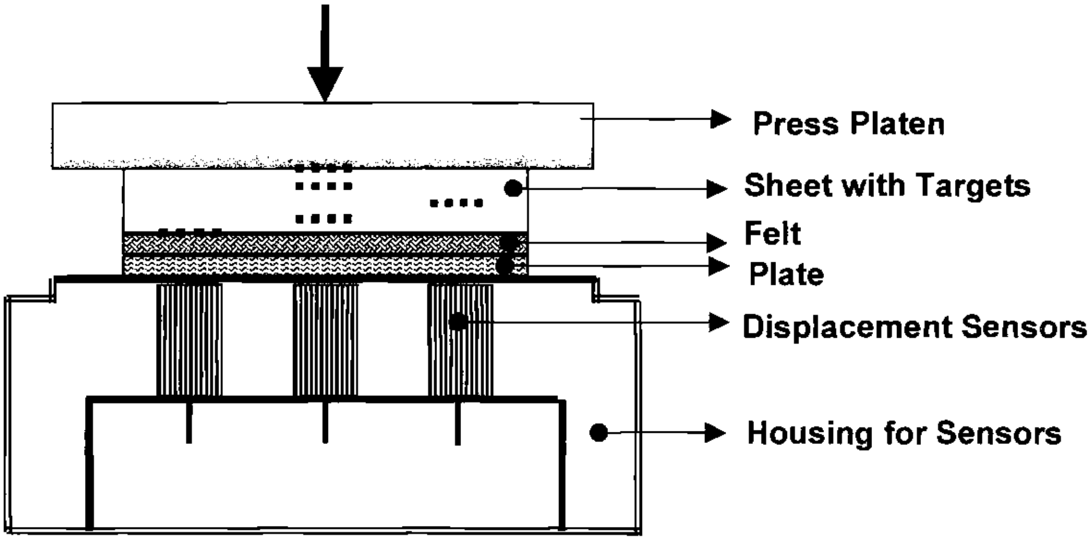

Figure 1. Experimental Setup of Dynamic Thickness Measurement System on the MTS Press

Figure 2. Sheet Thickness vs. Nip Time at Room Temperature

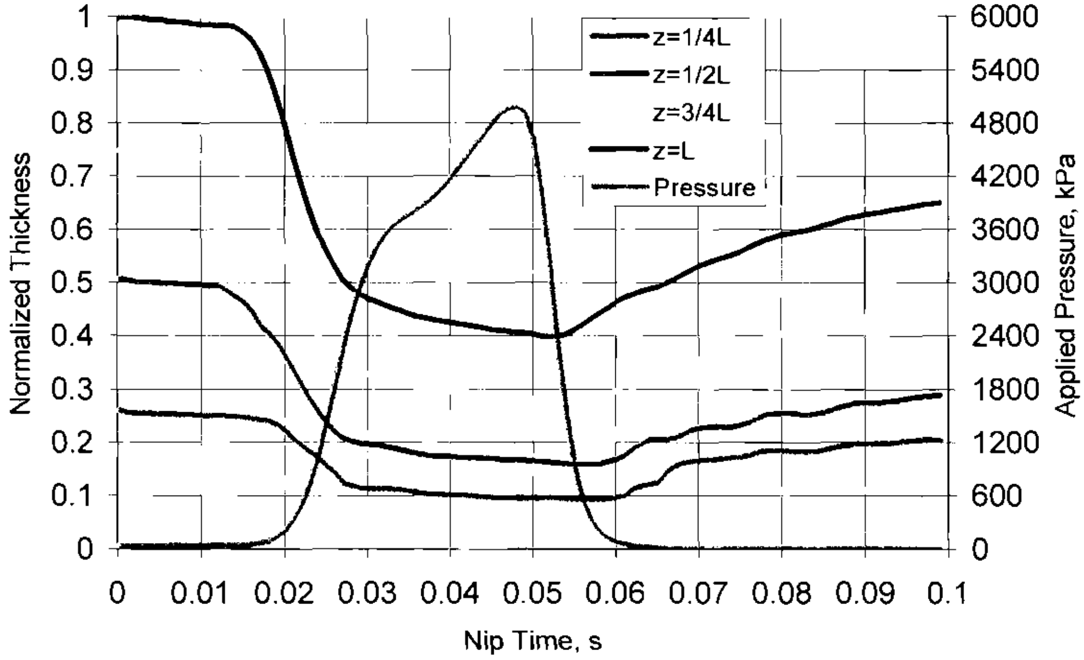

Figure 3. Sheet Thickness vs. Nip Time at Platen Temperature of $300^{o}C$

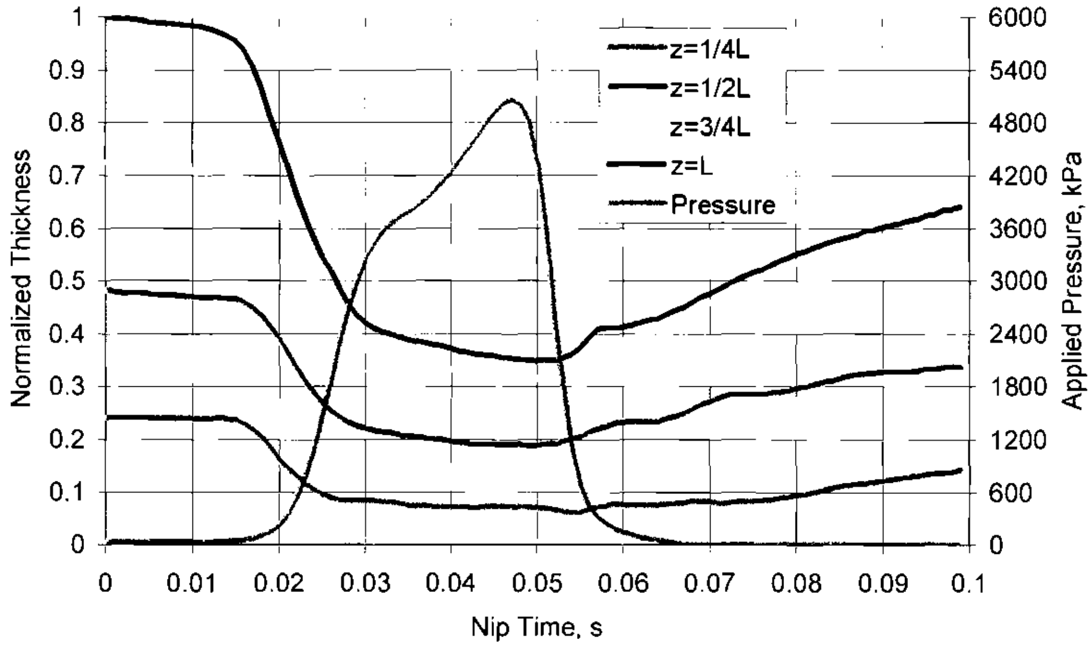

Figure 4. Compression Intervals in the Press Nip

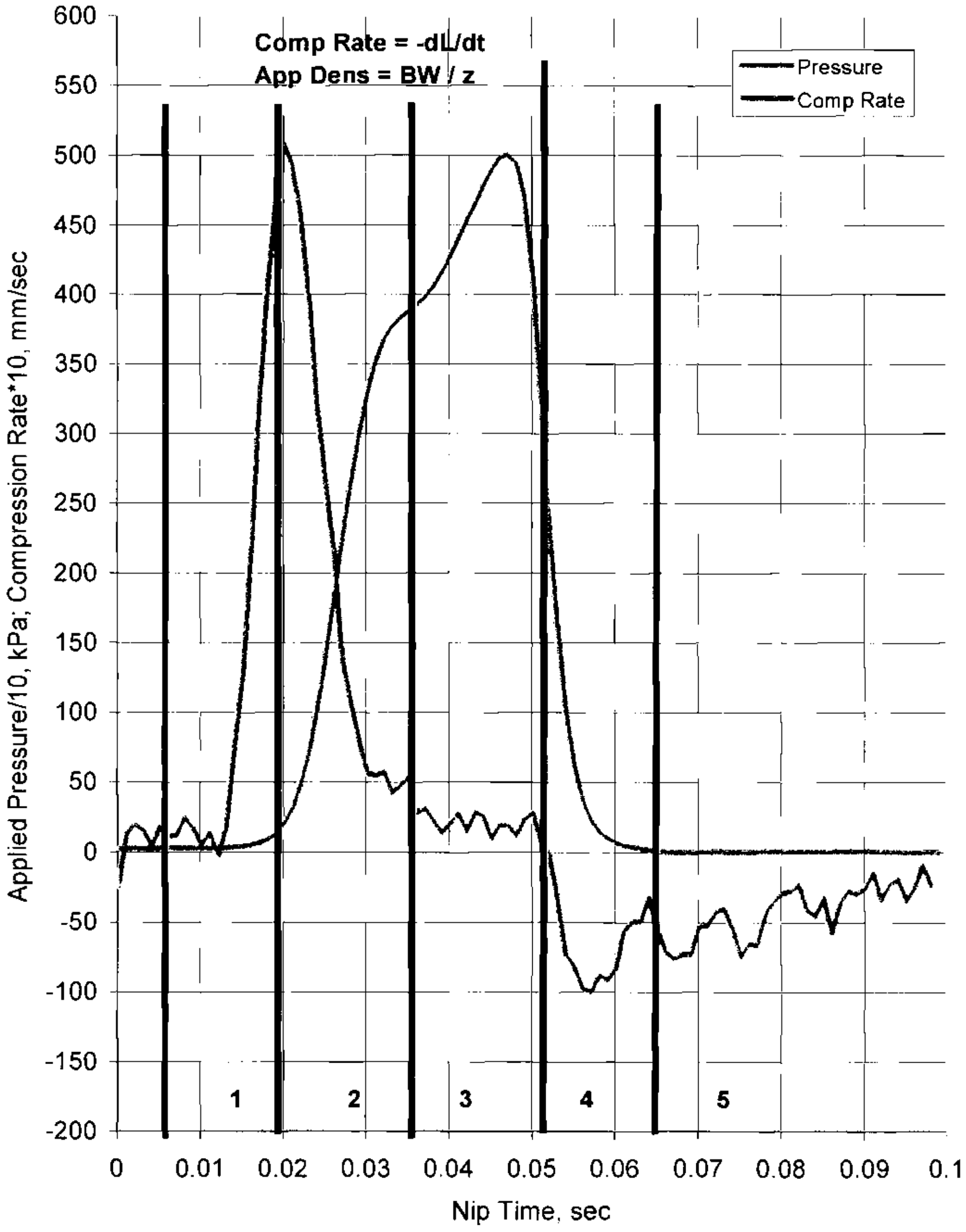

Figure 5. Experimental and Calculated Compression Rates for Pressing at Room Temperature

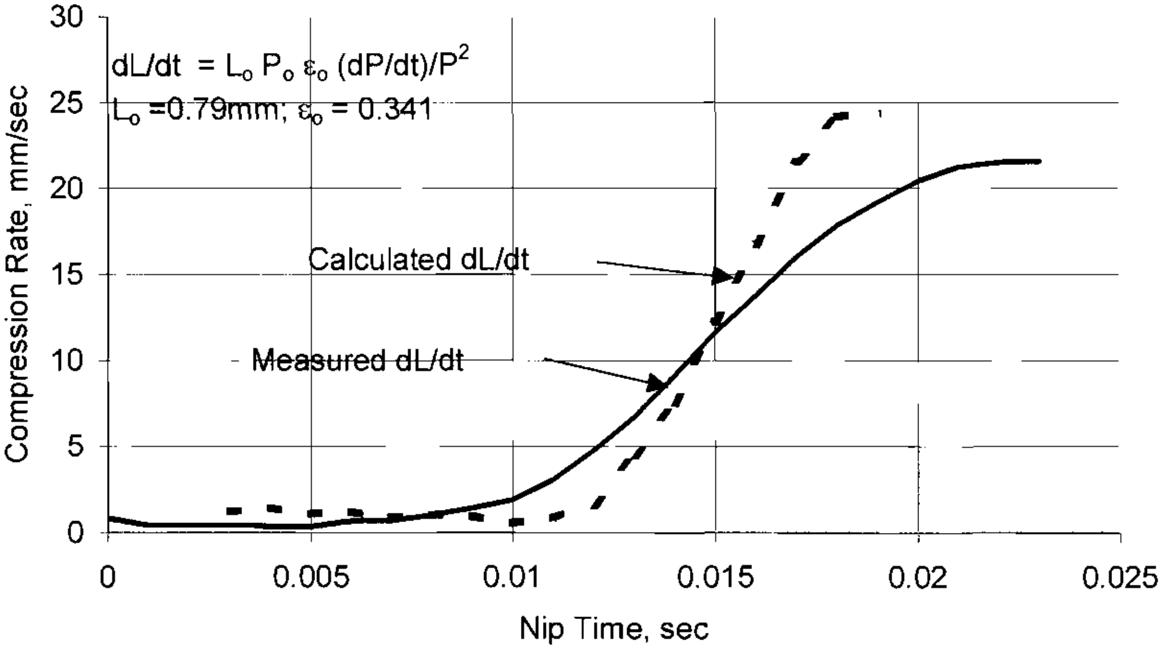

Figure 6. Sheet Temperatures vs. Sheet Thickness at Platen Temperature of 100°C

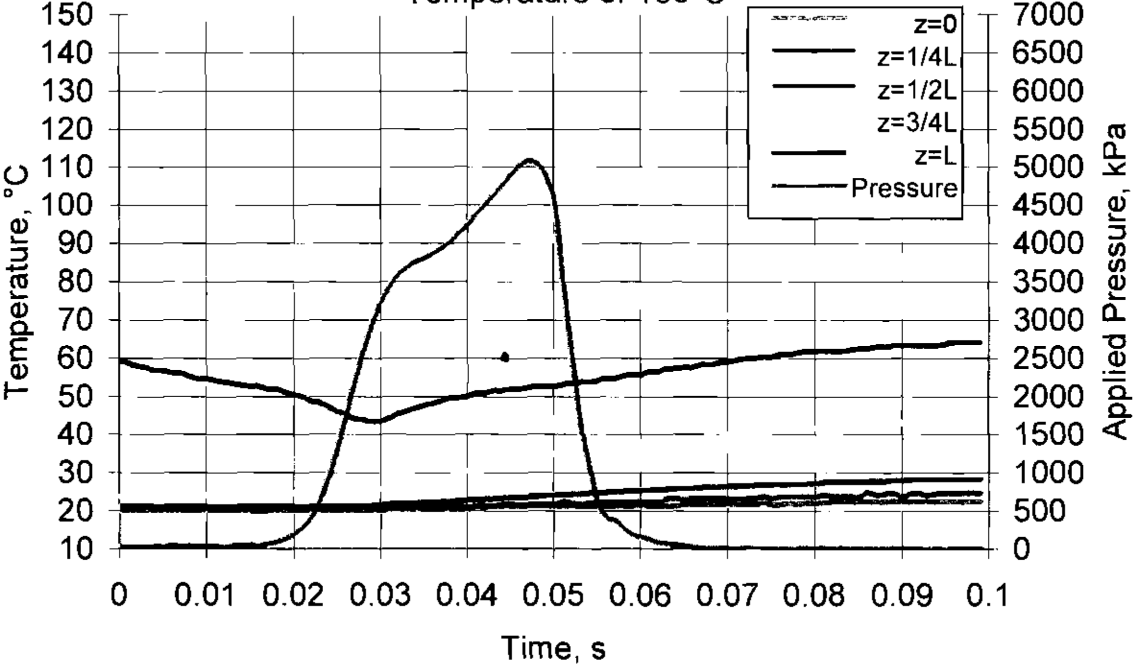

Figure 7. Sheet Temperature vs. Sheet Thickness at Platen Temperature of 300°C