Measurement of Paper-Shell Contact Coefficients

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ABSTRACT

This paper presents a study of paper drying using a newly developed laboratory drying apparatus. The process variables studied were shell surface temperature, sheet solids, and basis weight. The heat transfer rates and paper-shell contact coefficients were measured over a wide range of experimental data. The data from these trials show that paper drying undergoes a transformation of mechanisms that affect the shell-paper contact coefficient and hence the drying rate. At moisture ratios less than 1.0 and shell temperatures less than 150 °C, the paper drying follows the conventional drying pattern with paper-shell contact coefficients of 800 $W/m^{2o}C$ in the constant rate period and decreasing paper-shell contact coefficients in the falling rate period. At temperatures above 150 °C and higher moisture ratios the drying behavior is very different. In this region, there is an initially a high heat transfer rate that rapidly decays. It is proposed that this decrease in heat transfer and hence, shell-paper contact coefficient results from the formation of steam at the paper-shell interface. Once the paper reaches a dryness level where steam is no longer formed at the paper-shell interface, the drying rate and contact coefficient again increase. This later increase is followed by a final decrease in the heat transfer rate that closely follows that observed for sheets dried at lower shell temperatures. The overall drying behavior is highly dependent on the process variables and is explained by the proposed vapor formation at the shell-paper interface.

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INTRODUCTION

The objective of this project is to measure the heat transfer rate and determine the paper-shell transfer coefficient during paper drying. The principles guiding the design of the experimental system are that the drying system should simulate the processes occurring during commercial paper drying, it should be stable, easy to use, and yield reproducible data consistent with accepted literature values.

Based on heat transfer in conventional paper drying, the system selected uses a paper sheet held against heated surface by a dryer fabric. Although many methods are employed to dry paper, the most common uses a series of steam heated cylinders. In this system, steam condenses on the inner cylinder surface and the heat of condensation is transfer to the paper web, which is held against the outer surface with a dryer fabric.

Resistance to heat transfer from the condensing steam in the dryer cylinder to the paper includes the condensate layer, scale, the metal shell, and the contact coefficient between the shell and the paper. Of these, the contact coefficient is the most critical. Different studies, as described by Wilhelmsson, *et al.* (1), have reported that the contact coefficient accounts for from 35 % to 75% of the total heat transfer resistance.

Because of the importance of the paper-shell contact coefficient to heat transfer and its uncertainty, the majority of the experimental studies (1-8) on paper drying have focused on quantifying this parameter. These studies can be divided into machine trials, dynamic laboratory studies and static laboratory studies. As described by Wilhelmsson *et al.* (1), there are several advantages to static laboratory studies. The major advantages are that a laboratory system provides a defined environment, allows many different conditions to be studied and provides rapid drying data collection and analysis. A major result of these studies is finding that the contact coefficient is highly dependent on the water/solids ratio of the paper. For example, Wilhelmsson, *et al.* (1) found that the contact coefficient decreases from about 800 W/m$^{2\circ}$C to 200 W/m$^{2\circ}$C as the moisture ratio in the paper decreased from 1.0 g-water/g-solids to 0.2 g-water/g-solids. These studies also report that the contact coefficient tends to decrease with shell temperature (although there are conflicting findings in some of the papers on this effect), and is independent of fabric design and fabric tension within standard commercial ranges.

To determine the contact coefficient, the heat flux from the shell to the paper needs to be determined. Several methods have been used to determine the heat flux. Earlier solutions to determination of the heat flux, as employed by Rhodius and Gottshing (8), were based on comparing measured and calculated variables, such as moisture content. The contact coefficient was then adjusted until the measured and calculated heat fluxes agreed. More recently, Ahrens (3) used the Duhamel theorem, which is based on heat transfer into a semi-infinite slab using varying surface temperature, to calculate the paper-shell contact coefficient. Wilhelmsson, *et al.* (1) reviewed different experimental techniques to measure the contact coefficient and choose to use the Duhamel method developed by Ahrens.

The Duhamel theorem, as described by Ahrens (3), for a continuing changing surface temperature of a semi-infinite slab, which was initially at uniform throughout the slab, is given by equation (1).

$$\ddot{q}(\tau) = \frac{2k}{\delta} \int_{0}^{\tau} \sum_{n=0}^{\infty} [e^{-\lambda_n^2 (\tau - \tau')}] \frac{dT_s}{dt'} dt' \tag{1}$$

Here, $\ddot{q}$ is heat flux w / m^2, k is thermal coductiviy of metal shell, λ is summation term $= (2n+1)p / 2$, τ is dimensionless time $= (\alpha\ t / s^2)$, where s is the metal thickness, t is time and α is the termal diffusivity and τ' is time shifted.

Based on these studies, the Duhamel method was selected as a potential technique for determining the heat transfer coefficient. However, in the development of the Duhamel theorem, it is assumed that the cooling pulse induced by the paper on the dryer surface never reaches the opposite side of the cylinder and that the initial temperature throughout the metal slab is constant. Because of the uncertainty induced by these assumptions, heat transfer rates were also modeled using the explicit finite difference approximation of the fundamental heat transfer equation, shown in equation (2). Dewitt (9) presents a good development of this equation and of the explicit finite difference method.

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \tag{2}$$

Here, T is temperature and x and y are the dimensions.

If the system is one-dimensional in x, this equation can be written as an explicit form of a finite-difference equation as equation (3).

$$T_m^{p+1} = Fo(T_{m+1}^p + T_{m-1}^p) + (1 - 2Fo)T_m^p \tag{3}$$

Here, m is the deminsional subscript and p is the time subscript and $Fo = \alpha \Delta t / (\Delta x)^2$.

The two heat flux models described above were used to analyze the temperature data during paper drying. The models were written in Visual Basics for Applications. This allowed the Excel spreadsheet to serve as an input-output platform for the program. The associated graphs then can be quickly generated using Excel's chart feature. The two programs are in the form of modules that can be imported an Excel spreadsheet.

EXPERIMENTAL SYSTEM

The experimental system was designed to simulate heat transfer into the paper during a typical paper cylinder drying paper process. Figure 1 shows the experimental system designed for this study.

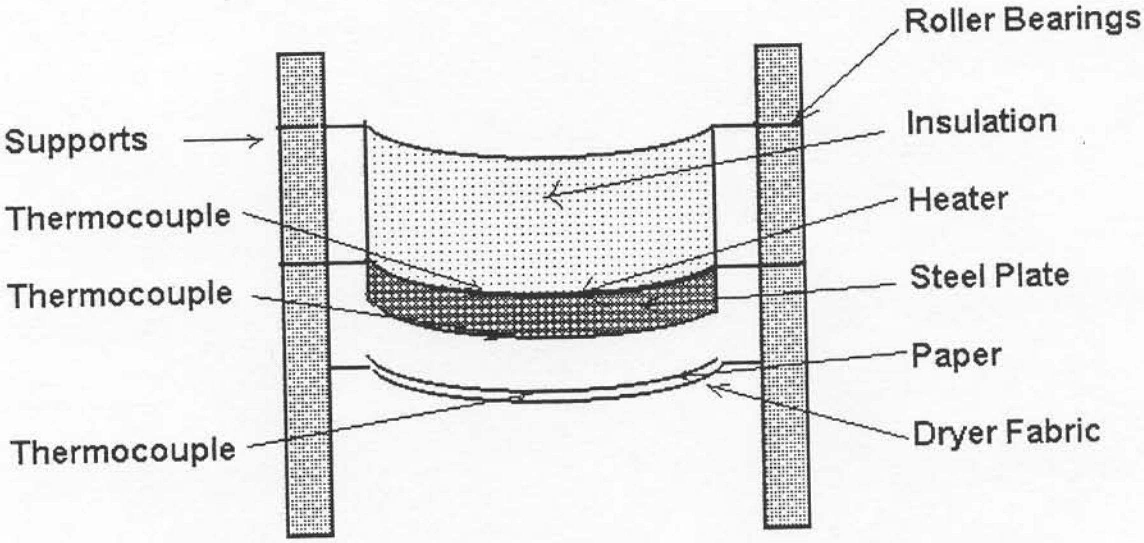


Figure 1, Experimental Paper Drying System:

The experimental system consists of a heated steel platen, a dryer fabric, and thermocouples. Data are collected using three type E thermocouples and a temperature data acquisition system manufactured by Computer Boards Inc. The thermocouples are located in the paper, at paper-heater interface and at the heater shell interface.

The paper is placed on the dryer fabric and a one-half inch 304 stainless steel plate, heated by a thermal-heating pad manufactured by Heater Designs. As the heater is lowered onto the paper, the data acquisition program is started.

The system was designed to simulate heat transfer on a paper dryer cylinder. The curvature of the metal shell used in these experiments is that of a 2 m diameter dryer cylinder. According to Stowe (10), the typical fabric tensions used on commercial dryers is in the range of 1.5 to 2.5 kN/m. Using Eqn (4) for the relationship between pressure and fabric tension, the fabric tension in these experiments was determined to be 1.1 kN/m, which is slightly less than that reported by Stowe (10) but within the range (0.5 kN/m to 1.7 kN/m) recommended by TAPPI (11) for newsprint machines.

$$\text{Pressure} = \text{Tension} \; / \; \text{Dryer Cylinder Radius} \qquad (4)$$

To calculate paper shell contact coefficient it is necessary to know the heat flux, and the paper and shell temperatures at the interface. The heat flux is obtained using the methods described in this paper. The shell temperature is obtained from a thermal couple embedded in the shell at the interface. This thermal couple was carefully designed and fitted into the shell to ensure that it accurately measures the shell interfacial temperature. The paper temperature is perhaps the key variable in this calculation. Techniques to determine this temperature include measuring the paper surface temperature after removal from the heated surface, as employed by Wilhelmsson *et. al* (1) or using a thermal couple embedded in the paper. In this study, the embedded thermal couple was employed to determine the paper temperature at the paper-shell interface.

EXPERIMENTAL RESULTS

Although several drying experiments were conducted, only representative drying curves are presented in this paper. These results show the general features of the drying system, provide a comparison of the Duhamel and the Explicit method, and demonstrate the reproducibility of the system.

Experimental Conditions:

For these drying experiments a soft wood kraft pulp was refined to a Canadian standard freeness of 340. Using Noble and Woods handsheet machine, handsheets at a basis weight of 40 g/m^2 to 80 g/m^2 were prepared. To facilitate the testing, the handsheets were cut into four sections of 10 cm x 10 cm. While full size handsheets could be used with the apparatus, this smaller sized allow for somewhat easier operation of the drying apparatus. Tests on different size handsheets showed no edge effects at this size.

The following figures show temperature measurements and heat fluxes for three typical paper drying experiments. The temperature on these figures is the metal surface temperature and the heat fluxes are calculated using both the Duhamel and the Explicit methods.

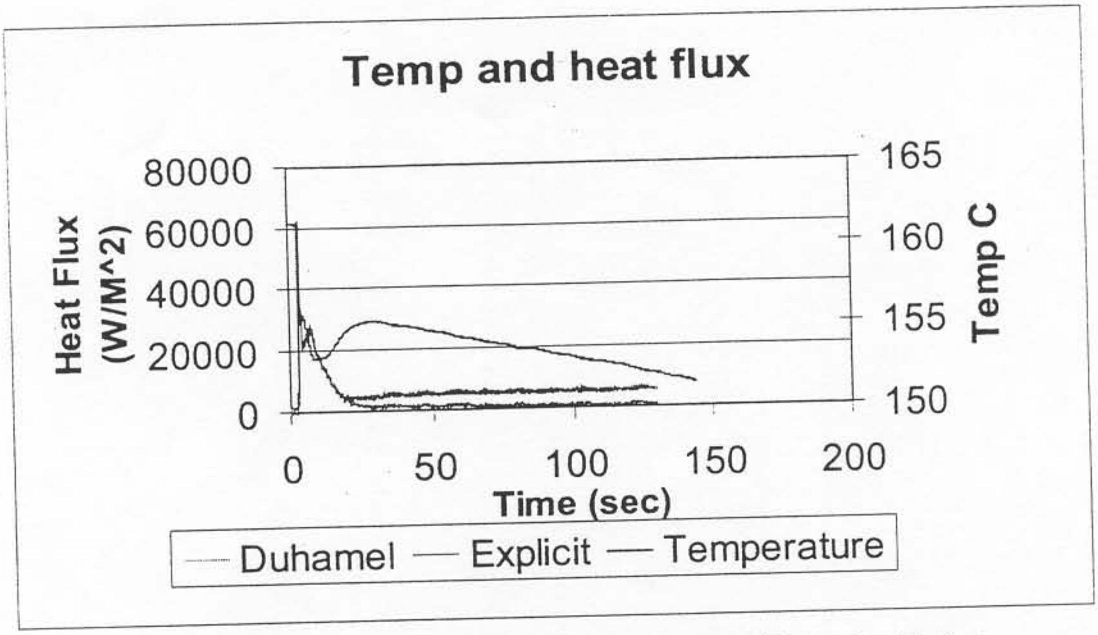


Figure 2, Typical Temperature and Heat Transfer Rates Sheet 40 g/M^2, 155 °C

The single temperature based Duhamel method and the dual temperature based Explicit methods were developed independently. The Duhamel method was tested by comparing the results from this method to those of the known analytical solution for a step temperature. Close agreement was found with these two techniques. Therefore, the Duhamel method correctly predicts the heat flux within the assumptions of uniform initial temperature and a semi-infinite slab.

In the above figure, the Duhamel and the Explicit methods show close agreement as long as the assumptions of the Duhamel method are maintained. However, once the temperature wave from paper drying reaches the opposite side to the heated slab, the Duhamel prediction deviates from that of the Explicit method. Because the Duhamel method agrees with known analytical solutions and the Explicit and Duhamel methods are in close agreement, as long as all the Duhamel assumptions are valid, the Explicit method can be assumed to accurately predict the heat transfer rates.

Effects of Shell Temperature and Basis Weight on Contact Coefficient:

The shell temperature is a key variable in paper drying and although most researchers report a decrease in contact coefficient with increasing shell temperature, there is no accepted explanation for this phenomenon. In this study heat transfer rates were measured with shell temperatures from less then 100 °C to about 160 °C.

Shown in Figure 3 is the contact coefficient versus time for a 65 g/m^2 sheet dried at initial shell temperature of 114 °C. The drying curve was also obtained for this sheet and is shown in Figure 4. About 5 to 10% of the energy transferred to the sheets during drying was lost through convention and these figures were adjusted to account for this loss. The data from the Figures 3 and 4 can be combined to present contact coefficient as a function of the solids ratio as shown in Figure 5.

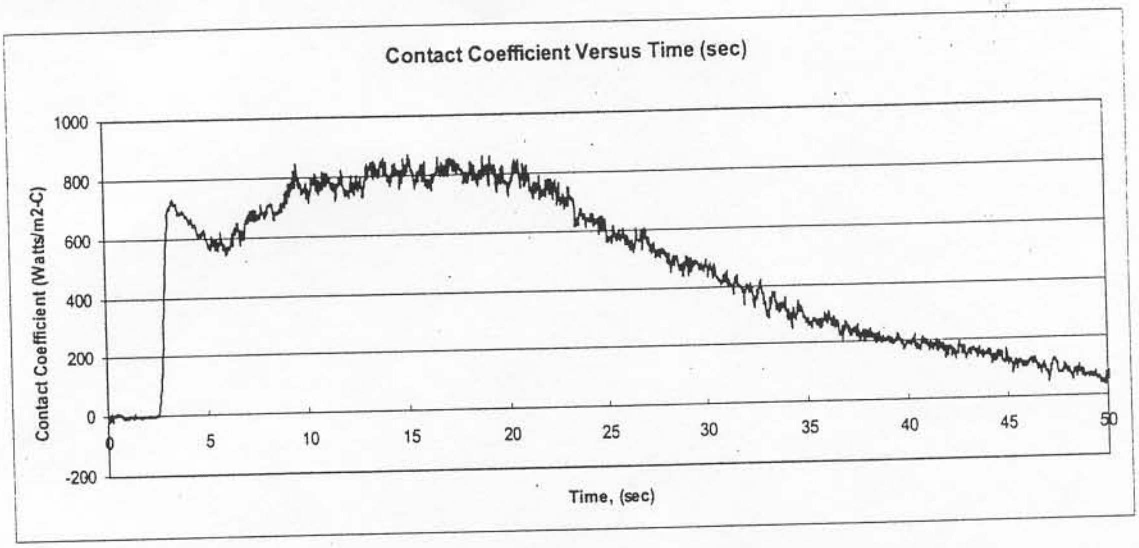


Figure 3, Contact Coefficient versus Time for 65 g/M^2 with Initial Temperature 114 °C

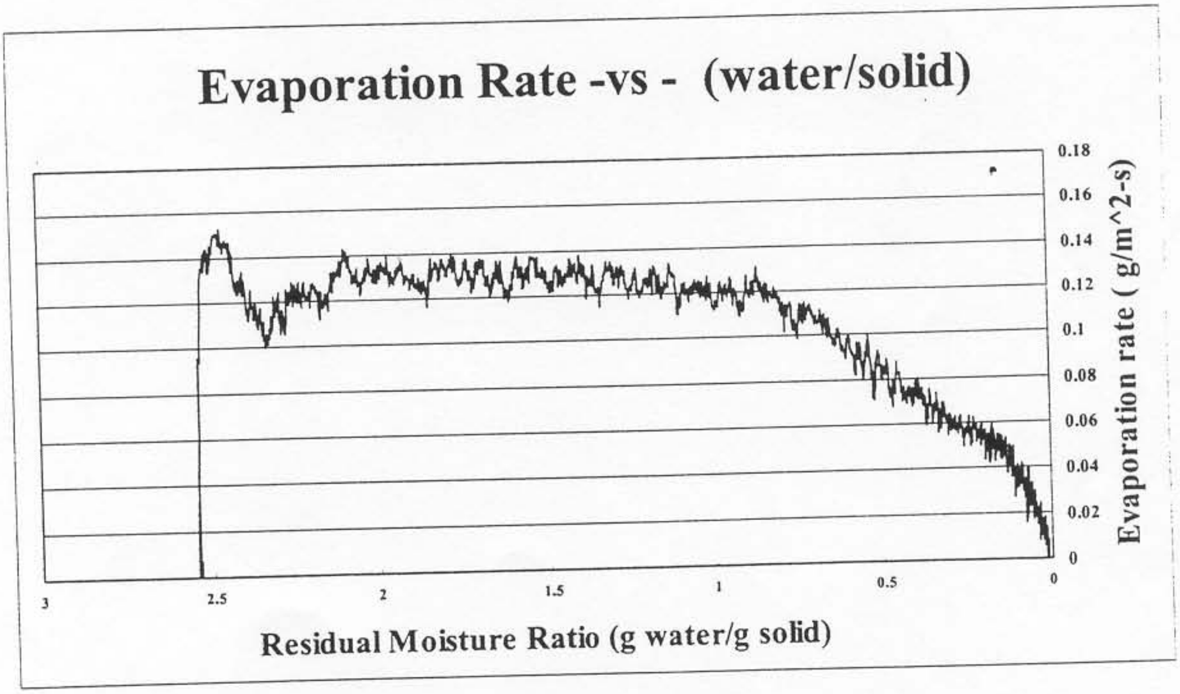
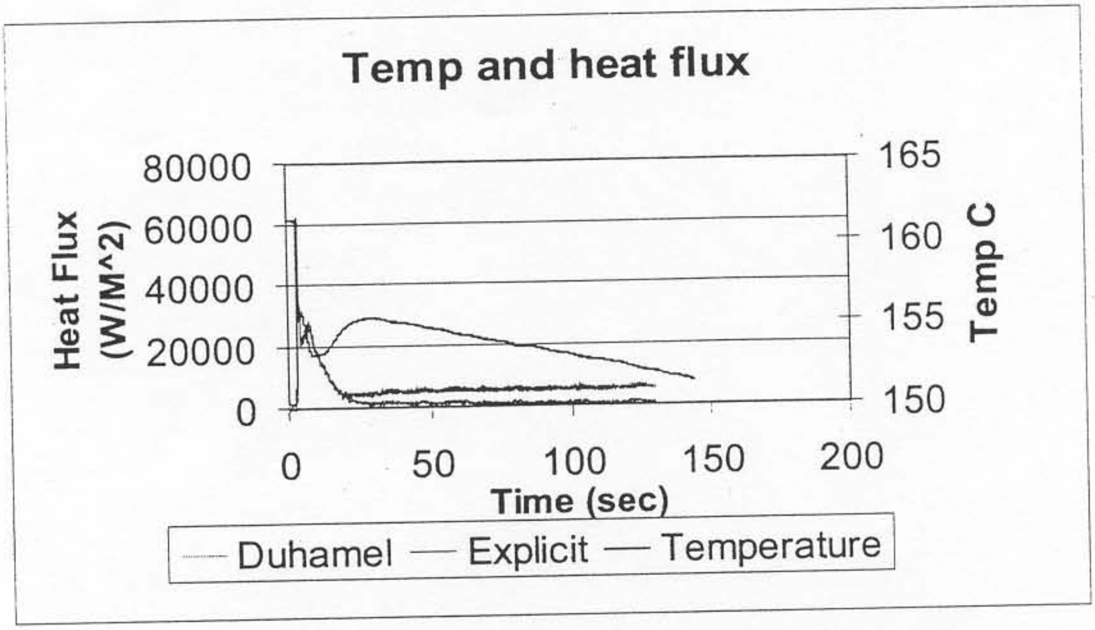


Figure 4, Drying Curve for 65 g/M^2 with Initial Temperature 114 °C



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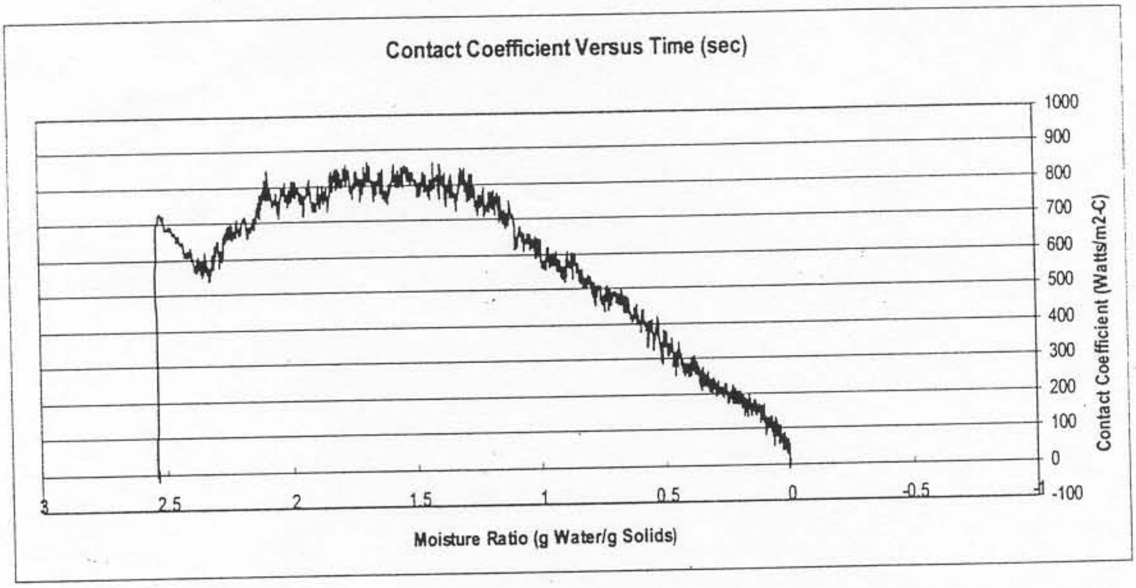

Figure 5, Contract Coefficient for 65 g/M^2 versus Moisture Ratio with Initial Temperature 114 °C

Figure 5 shows the typical behavior of the paper-shell contact coefficient. During the constant drying rate, the coefficient is approximately 800 W/m^{2}°C. During the falling rate period, the contact coefficient linearly decreases from 800 W/m^{2}°C to about 50 W/m^{2}°C. This behavior is fairly consistent over a temperature range from 90 to 150 °C and basis weights from 40 g/m^2 to 80 g/m^2. The heat transfer coefficient was not highly dependent on the shell temperature. However at temperatures above 150 °C and moisture ratios greater than 1.0, another region of drying behavior is observed. This region is shown in Figure 6 where an 80 g/m^2 sheet was dried with an initial shell temperature of 160 °C.

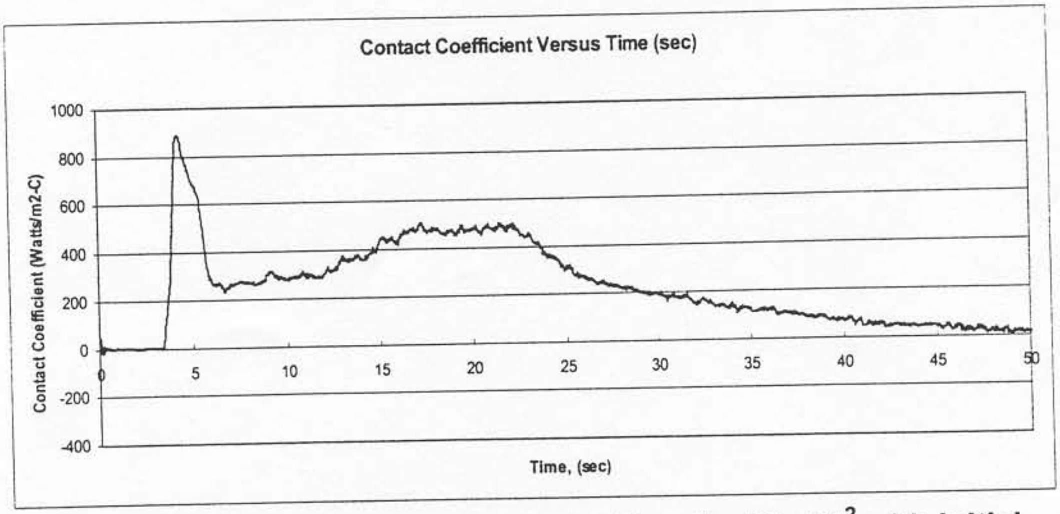

Figure 6, Contact Coefficient versus Time for 80 g/M^2 with Initial Temperature 160 °C

At these conditions there is initially rapid heat transfer and a high paper-shell contact coefficient. This is followed by a fast decrease in the heat transfer heat and the coefficient. The heat transfer rate and coefficient then gradually increase until the paper reaches the falling rate drying region. In this region the contact coefficient agrees closely with those obtained for either dryer sheets or at lower shell temperatures.

DISCUSSION

The experimental accuracy of the above technique for measuring heat transfer rates and contact coefficients was confirmed by comparing the results obtained with the Explicit method to those obtained with the Duhamel method. The agreement between the heat transfer rates of the Duhamel and the Explicit method is an excellent indication of the accuracy of the heat flux calculations. The total energy transferred to the paper can be calculated using three independent methods. These are: 1) energy transferred based on the temperature measurements, 2) energy transferred based on the total energy required to heat and dry the paper and 3) energy transferred based on the temperature change in the steel shell. These three different measurements are typically within 10%. Because there is some loss of heat from the paper through convection, the energy required to dry the paper is usually 5 to 10% lower than that obtained from the other two measurements.

The paper-shell contact coefficients calculated in this study agree closely with published literature values. For example in Figure 5 the paper-shell contact coefficient decreasing from 800 $W/m^{2o}C$ to about 50 $W/m^{2o}C$ as the paper dries. This is within the typical literature values of 800 $W/m^{2o}C$ to 200 $W/m^{2o}C$ as reported by Wilhelmsson (1). However, Wilhelmsson (1) only reported that the contact coefficient decreased. In the above experiments, it is shown that this decrease is linear function of the moisture ratio during the falling rate phase of paper drying. During the constant drying period, the contact coefficient remained relatively constant at 800 $W/m^{2o}C$. Over the basis weight range studied (40 g/m^2 to 80 g/m^2), the contact coefficient was not a function of basis weight.

At temperature in excess of 150 °C and moisture ratios greater than 1.0, another type of drying behavior is observed. This behavior can be explained by the formation of a steam vapor layer at the paper-shell interface. The heat transfer rate is very rapid until the vapor layer forms, after formation of this layer there is a rapid decrease in the heat transfer rate, followed a gradual increase. The decrease is believed to be due the formation of the vapor layer. As the paper dries this vapor layer gradually decreases and the heat transfer rate increases. Once the paper reaches the falling rate period, the drying behavior and heat transfer coefficients closely agree with those obtained for sheets dried either with lower initial solids or at lower initial shell temperatures.

NOMENCLATURE

k	thermal coductiviy of metal shell, W / m K
s	the metal thickness, m
t	time, s
α	thermeal diffusivity, m^2 / s
Δt	change in time, s
Δx	change in x dimension, m
$\ddot{q}$	heat flux, W / m^2
τ	dimensionless time, $(\alpha\ t / s^2)$
τ'	time shifted

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