Development of Experimental Techniques and Measurement of Paper-Shell Contact Coefficient

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This paper describes the development of an experimental technique for measuring the paper-dryer shell contact coefficient during paper drying. The transfer of heat form the pressurized steam to the wet paper during paper drying involves several resistances. These include the condensate layer, scale on the inside dryer surface, the metal shell, and the metal-paper interface. With a proper functioning dryer, the resistance at the metal-paper interface is the most significant of these factors. Several variables affect this coefficient. These include the dryer temperature, felt tension, refining, type of pulp fibers, and the cleanliness of the dryer surface. Unfortunately, the nature of these effects is not precisely known because the published studies are limited and many times contradictory.

In this study, a bench-scale laboratory dryer was constructed and using heat transfer theory, a numerical technique was developed to determine the heat transfer rates into the paper during drying. The results from these measurements were compared to those determined using Duhamel's theorem for heat transfer into a semi-infinite slab. Duhamel's theorem is the principal technique used to determine paper-shell contact coefficients. The results of this comparison show that a fundamental analytical approach using a finite difference method provides results comparable to those obtained using Duhamel's theorem.

INTRODUCTION

The objective of this project is to develop a paper drying system. The principles guiding the design 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 during conventional paper drying, the system selected uses a paper sheet held against heated surface by a dryer fabric. This choice is based on the following analysis. 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.

As shown in Figure 1, paper drying on cylinders can be divided into four phases (1). In phase I, the paper contacts the dryer without fabric contact; in phase II, the paper is held against the dryer can by the fabric; in phase III, the felt leaves the paper with the paper remaining in contact; and in phase IV, the paper travels between individual dryer cans. This process has been studied using both experimental techniques and dynamic models [2]. Results from these studies show that the majority of the drying energy is transferred into the paper in phase II, where the dryer fabric holds the paper against the dryer cylinder.

Resistance to heat transfer from the condensing steam 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. [2], have reported that the contact coefficient accounts for 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 [1-10] on paper drying have focused on quantifying its magnitude. These studies can be divided into machine trials, dynamic laboratory studies and static laboratory studies. 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 for rapid drying data collection and analysis. One finding of these studies is that the contact coefficient is highly

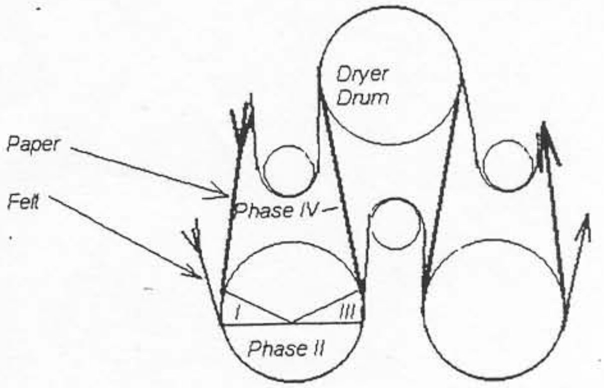

FIGURE 1. Four phases of paper drying on cylinderical drying drums.

dependent on the water/solids ratio of the paper. For example, Wilhelmsson et al. [2] found that the contact coefficient decreases from about 800 W/m²-°C to 200 W/m²-°C as the moisture ratio in the paper decreased from 1.0 g water/g pulp to 0.2 g water/g pulp. Wilhelmsson et al. also found that the contact coefficient was independent of shell temperature, fabric design and fabric tension within standard commercial ranges. However other researchers have reported conflicting results on the effect of surface temperature on the contact coefficient. For example, Redfern [3] reported that the contact coefficient increased with increasing surface temperature, while Meinecke et al. [4] reported that the contact coefficient decreased with increasing surface temperature.

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, as employed by Rhodius and Gottshing [5], 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 [6] used Duhamel's 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. [2] reviewed different experimental techniques to measure the contact coefficient and also choose to use Duhamel's theorem. Duhamel's theorem appears to be the preferred method of calculating the heat fluxes and contact coefficients.

Duhamel's theorem, as described by Ahrens [6], for a continuing changing surface temperature of a semi-infinite slab, which was initially at uniform throughout the slab, is given by equation (1).

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

Here ¨q is heat flux W/m². k is thermal conductivity of metal shell, λ is summation term = (2n +1)p/2, τ is dimensionless time = (α t/s²), where s is the metal thickness, τ is time and a is the thermal diffusivity and τ' is time shifted.

Based on these studies, Duhamel's theorem was selected as a potential technique for determining the heat transfer coefficient. However, in the development of the Duhamel's 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 determined by applying an explicit finite difference method to the fundamental heat transfer equation, shown in equation [2]. Dewitt [11] presents a good development of this equation and of the explicit finite difference method.

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

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).

$$T_m^{p+1}-Fo\left(T_{m-1}^{p}\right)+(1-2Fo)T_m^{p} \qquad (3)$$

Here m, is the dimensional subscript and p is the time subscript and Fo = αΔt/(Δx)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 2 shows the experimental system designed for this study.

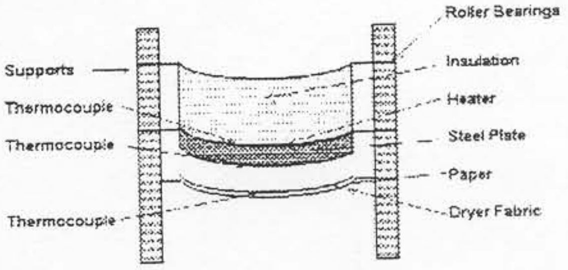

FIGURE 2. Experimental paper drying system.

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 at the surface of 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 1.83 m (6 ft) diameter dryer cylinder, a common commercial size. The total weight applied on the laboratory paper during drying was 8 Kg (17.6 lb). This gives a pressure of 1.2 kPa (0.172 psi). Using Eqn (4) the fabric tension is then 1.1 kN/m.

Pressure = Tension/Dryer Cylinder Radius (4)

Depending on machine speed, the recommended fabric tensions for newsprint range from 0.5 to about 2.0-kN/m [12]

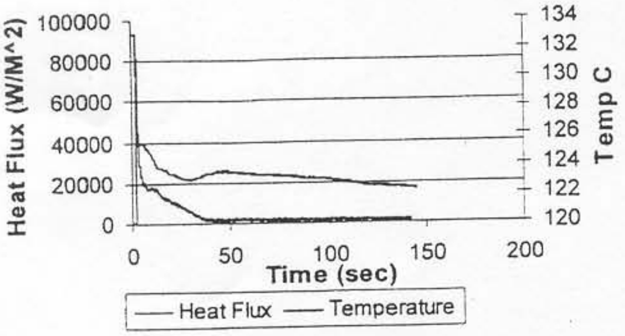

FIGURE 3. Surface Temperature and Explicit Heat Flux with an Initial Surface Temperature of 133 °C and with Precooling

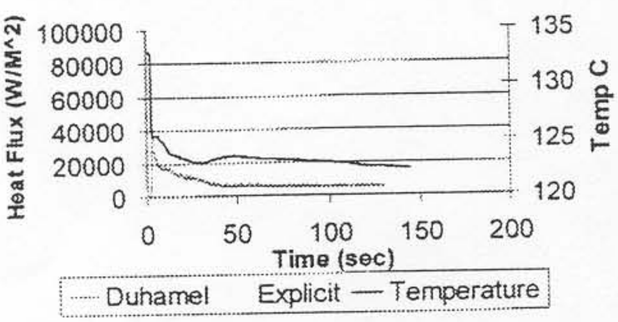

FIGURE 4. Comparison of Duhamel and Explicit Heat Fluxes for Data Shown in Figure 3.

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 were made for this study. 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 with different size handsheets showed no edge effects due to the use of the 10 cm x 10 cm handsheets.

RESULTS

Although several drying experiments were conducted only two are shown in this report. The experimental results show the general features of the drying system, provide a comparison of the Duhamel and the Explicit method, and demonstrate the experimental accuracy of the system.

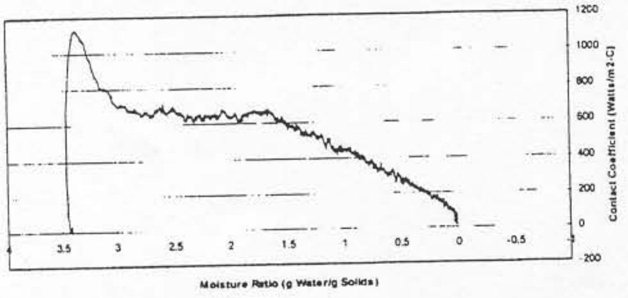

FIGURE 5. Contact Coefficient Based on the Explicit Method for Drying Experiments Described in Figures 3 and 4.

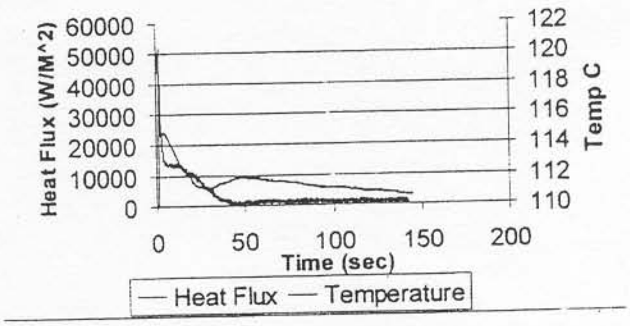

FIGURE 6. Surface Temperature and Explicit Heat Flux with an Initial Surface Temperature of 120 °C and with Precooling

The two assumptions of the Duhamel's theorem are first, the metal is at a uniform temperature throughout the metal and second, the cooling wave never reaches the backside of the metal. When the Duhamel's theorem is used, it is important that both of these criteria are met. Since an embedded heater normally heats the metal surface, the first assumption is difficult to achieve. However, turning the heater off and letting the metal cool helps satisfy this assumption. The second assumption is met by constructing the heater out of significantly thick metal. This helps assure that the cooling wave will not significantly affect the backside temperature.

The Explicit method requires that the initial temperature of the metal surface be known. However, this assumption does not require a uniform metal temperature. This initial condition is met by assuming an initial linear temperature profile in the metal surface and by letting the metal cooled so that the temperature difference between the heated surface and paper surface is quite small. This ensures that any nonlinear behavior will have a minimum effect on the heat transfer calculations.

Figures 3 through 8 show temperature measurements, heat fluxes for two papers drying experiments and contact coefficients for the two paper drying experiments. The temperature on these figures is the metal surface temperature and the heat fluxes are cal-

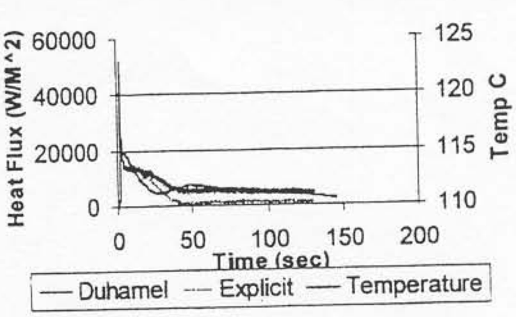

FIGURE 7. Comparison of Duhamel and Explicit Heat Fluxes for Data Shown in Figure 6

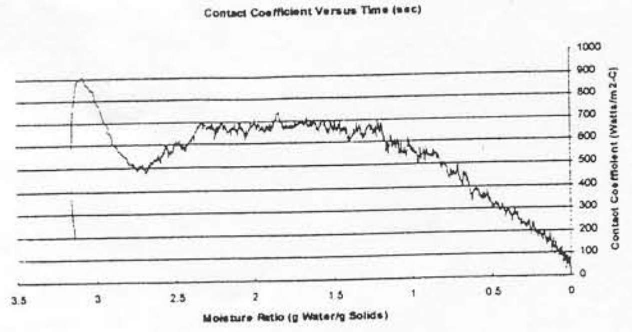

FIGURE 8. Contact Coefficient Based on the Explicit Method for Drying Experiments Described in Figures 6 and 7.

culated using both Duhamel's theorem and the Explicit finite difference method.

EXPERIMENTAL ACCURACY

Evaluation of Duhamel's theorem, shown in Eqn (1), requires that this expression be numerically integrated at each point in time. During the development of the numerical integration program for Duhamel's theorem, the results of the numerical integration were compared to those of the known analytical solution of a step change in temperature. Since both the analytical solution and the numerical technique produced the same heat flux, this confirmed that Duhamel's theorem was correctly evaluated and that it correctly predicted the heat flux. When the conditions of the Duhamel's theorem are satisfied, the agreement between the heat transfer rates of the Duhamel and the Explicit method provides an excellent indication of the accuracy of the heat flux calculations.

As shown in the above figure, there is somewhat more point to point variation using Duhamel's theorem than there is using the finite difference method. But more importantly, there is a deviation between the two methods once the cooling wave reaches the far side of the metal plate. This can be avoided by using a metal plate with a thickness such that the cooling wave never reaches the far side. However, a larger metal plate makes the initial condition of uniform temperature more difficult to satisfy and for this experimental system, a large weight would increase the felt tension to a commercially unrealistic range. If the assumptions of the two experimental techniques are met, both techniques yield similar heat transfer results.

To further test the accuracy of the experimental method the integral of the heat flux was compared to the energy required to dry the paper based on a gravimetric measurement of the amount of water evaporated. This comparison is presented in Table 1 for the two experiments described in this paper.

With this experimental system, the energy required to heat the water and paper and to evaporate the water is normally 80 to 90% of that calculated based on the heat flux. This difference may be due to convention losses during drying of the paper or energy transferred into the felt.

Table 1. Comparison of Calculated from Heat Flux to that Calculated from Gravimetric Measurement

Experiment Paper, Initial Drying Temperature	Energy Transferred Based on Integral Heat Flux	Energy Transferred Based on Gravimetric Measurement
40 g/m^2 at 133 °C	467,000 J/m^2	403,000 J/m^2
40 g/m^2 at 120 °C	413,000 J/m^2	347,000 J/m^2

The paper-shell contact coefficients that can be calculated from these figures and the shell and paper temperatures agree well with the literature values. For example in Figure 3, the temperature of the paper varied from 80 to 94 °C. This results in the paper-shell contact coefficient decreasing from 600 W/m^2-°C to about 100 W/m^2-°C as the paper dries. This is within the typical literature values of 800 W/m^2-°C to 200 W/m^2-°C reported by Wilhelmsson [2].

FUTURE WORK

These results demonstrate the accuracy of the experimental system; this includes the drying system, data acquisition system and heat flux calculations. On-going work on this project includes continually checking this system for errors, and improving the user friendliness of the program. Planned work includes quantifying the effect of other experimental variables and developing analytical and operational models.

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