Thermal Performance of Copy Papers During Fusing

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Abstract

The thermal performance of copy paper during fusing was studied by measuring the temperature and moisture content changes for a variety of different paper sheets. Sheet temperatures on the image and reverse sides were measured at different points in a continuous run Xerox photocopier. Sheet surface temperatures depend on basis weight, caliper, coating level and filler levels. Coated or highly filled sheets showed higher temperatures which persisted for longer times whereas those of lower densities were cooler. Moisture redistributions within the short time scale of fusing was insignificant.

An analysis of heat and moisture transport within the sheets subjected to a rapid thermal pulse was conducted. A mathematical model was developed using the equations of transient energy and moisture transport. The model equations were solved using the finite element method to predict temperature and moisture content profiles and their evolution within the paper sheets. Thermal conductivity, heat capacity and moisture diffusivity of copy paper sheets were measured in the laboratory and used as inputs to the mathematical model to predict the temperature and moisture response in the fusing section.

Excellent agreement was found between the model predictions and experimental temperature and moisture contents for several paper sheets under different conditions. The thermal conductivity and heat capacity are the critical parameters determining the temperature and moisture profiles and were strongly dependent on sheet structure.

Introduction:

Several processes subject paper sheets to thermal pulses. In paper drying, wet saturated paper sheets are subjected to a high temperature pulse on one surface. The newer high intensity drying processes rely on augmentation of the conventional drying mechanisms by pressure and capillary driven flows through the webs [1]. Paper sheets are subjected to similar thermal pulses in laserjet printing and photocopying applications. Here, toner particles on the sheet surface are fused to fasten the image by raising the surface temperature beyond the toner glass transition point. The surface temperature and thermal energy in the sheet are important quantities which determine the quality of the image and performance of the paper.

Simula et al. [2] reported an investigation of the temperature response of a sheet subjected to a hot roll nip. Their mathematical model incorporated only the one dimensional transient heat conduction equation and as a result only the evolving temperature profiles within the paper sheets could be studied. Furthermore, the validity of their simulation is restricted to short times since moisture diffusion and convective transport processes become significant at longer times. A more comprehensive simulation of the transient thermal, moisture and pressure fields inside paper sheets traveling through a hot roll nip has been investigated by Bandyopadhyay et al. [3]. Their simulations considered the complete transient two-dimensional temperature, moisture and air flow velocity fields within the paper sheets as they traveled through the fuser nip. The anisotropy in the transport properties of paper sheets for the in-plane and Z directions was also incorporated in this study. The relevant energy, moisture and flow conservation equations were solved using a finite-volume method. The most important findings to emerge from this study were that the temperature and moisture content fields were critically dependent on the sheet properties. The investigations reported earlier were not supplemented by accurate measures of the paper sheet properties (thermal conductivity and others) nor were they verified by experimental measurements. In the present work, we use a simplified version of the earlier mathematical model and confirm its predictions with experimental measurements of sheet temperatures in a high speed digital copier.

Mathematical Model for Transport in the Fusing Section

We consider a paper sheet which is initially at equilibrium at known moisture and temperature conditions, traveling through a nip consisting of hot and cold rollers as shown in Fig 1. The two rollers are kept at constant but different temperatures and expose the sheet to a temperature pulse on its surface as it moves through the nip. The paper sheet is idealized as a porous hygroscopic medium for analysis of the transport processes. The most important variables are the temperature $T(t,x,z)$ and the moisture content $q(t,x,z)$ fields. Since the pore space present in the paper sheet can hold water vapor, the concentration field $c(t,x,z)$ is also relevant. Although we track the evolution of these three fields, experimentally measurable quantities are usually the temperatures at the top and bottom surfaces and the energy and moisture transferred to the environment. Our new model is enhanced compared to the earlier one of Bandyopadhyay et al. [3] because we consider the dynamics of the vapor space coupled with the moisture content of the fibers in the sheet through a separate diffusion mechanism.

Table 1

	Paper Thickness, mm	Ash content, %	Specific Heat, J/(gK)	Density, g/cm^3	Thermal Conductivity, W/(cmK)	Thermal Diffusivity, cm^2/s
1	0.1368	8.69	1.55	0.773307	0.001094	0.000913

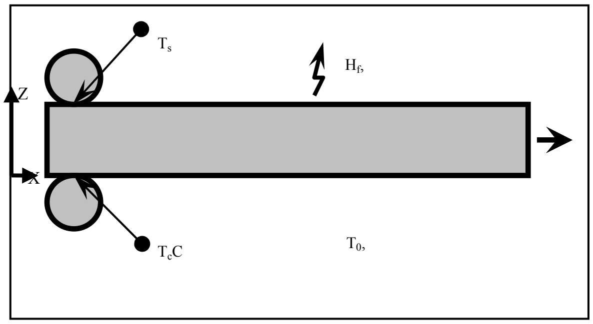

Fig. 1. Schematic of model domain and temperatures and external heat and mass transfer coefficients.

Model Equations

The equations for transient moisture transport are given below for the water in the pore space and fibers [4].

$$\varepsilon \frac{\partial c}{\partial t} + \rho \frac{\partial q}{\partial t} + \varepsilon \nabla . cv = D_p \nabla^2 c \tag{1}$$

$$\frac{\partial q}{\partial t} = \nabla [D_q \nabla q] + k_i (q_{sat} - q) \tag{2}$$

The above equations allow for water vapor transport by diffusion and convection within the pore space and diffusion locally between the fibers and the pore space. When the time scale for diffusion within the fibers is small, e.g. when the fiber phase is relatively thin, local equilibrium may be assumed [3]. However, local equilibrium of moisture in non-isothermal situations is not likely to be valid although the fiber and pore spaces may be assumed to have the same temperature on account of the relatively high thermal conductivity of the fibers. The average thermal conductivity of the sheet is denoted by k_p and heat capacity by c_p. The energy equation is then given by

$$\rho_p C_p \frac{\partial T}{\partial t} + C_{p,a} \nabla . (\rho v T) = k_p \nabla^2 T + \rho_p \frac{\partial (\lambda q)}{\partial t} \tag{3}$$

Darcy's law along with an overall mass conservation (continuity) equation closes the above system of equations (see [3]).

Initial and Boundary Conditions

The paper sheet is assumed to be in equilibrium with its surrounding environment and is at a moisture content given by q_0 and temperature T_0, both of which are uniform throughout the sheet.

As the sheet travels through the nip region, the top surface is subjected to an increase in temperature to T_h whereas the lower surface remains at T_0. After the sheet leaves the nip region, the environment is at the initial temperature T_0 but heat and moisture can be transported out of both these boundaries. The relevant rates of transport at the boundaries are given by the heat and mass transfer coefficients which are assumed to be known. The energy and moisture fluxes at the two boundaries are given by the following equations.

$$-k_p \nabla T = h_f (T_s - T_0) \tag{4}$$

$$-D_p \frac{\partial c}{\partial z} - \rho_p D_q \frac{\partial q}{\partial z} = k_f (c_s - c_0) \tag{5}$$

The surface temperature and surface vapor concentration are denoted by T_s and c_s respectively. The surface vapor concentration is an additional variable in this equation which is defined as the value that is at equilibrium with the paper sheet at its local moisture content, q_s. The following equation of equilibrium defines and completes this model.

$$q_s = f(c_s, T_s) \tag{6}$$

The equilibrium moisture-humidity relationship has been denoted by $f(c_s, T_s)$ in the above equation.

Model Parameters

For the purpose of the simulation, we used the following model parameters given in Table 1. The paper sheet thickness, porosity and other parameters for a baseline case were drawn from actual measurements of the thermal conductivity [5, 6] and heat capacity of coated and uncoated copy paper. The other parameters were obtained from indirect or direct measurements of conditions inside typical copiers [3]. Also, for the purposes of our simulation, we considered only a one dimensional solution to the above model equations although our model implementation was fully two-dimensional.

MODELING RESULTS

Our study of the sheet response was characterized by some key variables that can be measured easily. These correspond to: the sheet surface temperature, the average sheet temperature, the average moisture content and how these parameters vary with sheet properties. The key sheet properties we varied were: sheet thickness, sheet density, sheet thermal conductivity and heat capacity. We considered also the case of a coated (composite) sheet which was modeled as a sheet consisting of two layers of different properties.

Fig. 2 shows the temperature at the point of contact between the hot roller and the sheet (denoted by T_h). This temperature rises rapidly to the hot roller temperature, remains there as the nip travels over the surface and decreases back to the ambient value after the nip.

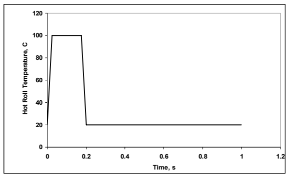

Fig 2. Temperature profile in contact point of hot roller and paper sheet

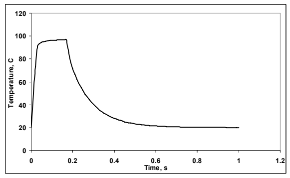

Fig. 3. Surface temperatureas a function of time

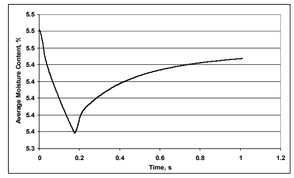

Fig. 6. Average moisture content in paper sheet

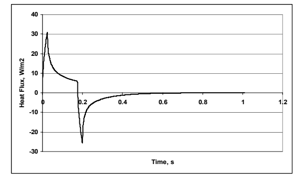

Fig. 7. Heat flux on top surface of paper sheet

Fig. 3 shows the temperature of the sheet's surface as a function of time as it travels through the nip region. The surface temperature increases rapidly to the roller temperature as shown in this figure. The cool-down of the surface is much slower because it is governed primarily by the surface heat transfer coefficient in the after nip region. Also shown in this figure are the heat-up and cool-down curves for sheets of different thermal conductivities. Increased thermal conductivity leads to rapid heating and similarly, to faster cooling since heat is able to move relatively fast through the sheet thickness. The increase in surface temperature controls the fusing process and it is seen that for the range of thermal conductivities considered here, the heating-up profile is satisfactory. The dynamics of the cooling curve determines the time that the surface remains hot for the fusion process. The thermal conductivity of the sheet seems to control the cooling curve to a greater extent than the heating curve.

Fig. 4 shows the complete two dimensional temperature field within the paper sheet at a time when the sheet has almost completed its travel. That the thermal conductivity has a significant influence on the extent of penetration of the temperature field is obvious. Higher thermal conductivity also results in significant heating of the bottom side of the sheet and consequent energy loss.

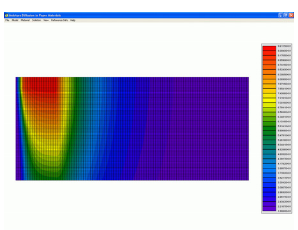

Fig. 4. Temperature distribution in paper sheet

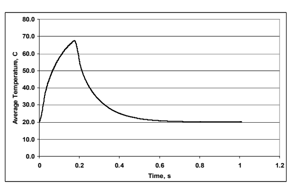

Fig. 5. Average temperature of paper sheet

Figs. 5 & 6 show the average temperature and average moisture content within the sheet for these conditions. These averages are calculated based on the one dimensional profiles through the thickness. The average temperature rises rapidly due to heating and cools after exposure to the nip. The moisture content decreases as sheet heats up but since moisture is mostly reabsorbed into the sheet as it cools down, the net loss in moisture content is relatively small.

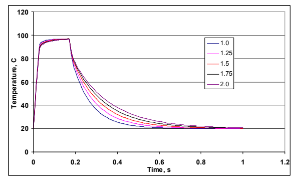

Fig. 8. Temperature of top surface of paper sheet for different values of specific heat (J/gK)

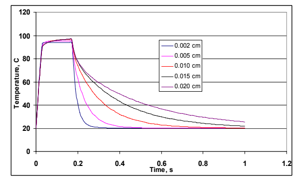

Fig. 9. Temperature of top surface of paper sheet for different values of sheet thickness

Fig. 7 shows the heat flux to the top surface of the sheet during the travel. The flux rises rapidly within a short time interval corresponding to the rise time of the contact temperature. This increase is because the sheet's surface is much lower than the hot roller temperature during this time. The flux decreases after the surface reaches the hot roller's temperature because the gradient in temperature at the surface has moderated during this time interval. The surface contact temperature drops when the sheet leaves the nip resulting in a steep decrease in the heat flux. The flux becomes negative, i.e. the sheet begins to lose heat to the surroundings in the after-nip region. The heat loss to the environment moderates as the surface cools to the ambient temperature, showing the slower exponentially decreasing negative heat flux in the after nip region.

Fig. 8 shows the top surface temperature evolution for sheets of different heat capacity and density. We observe that higher heat capacities and densities tend to damp the rise in temperature and tend to damp the dynamics. Both heat-up and cool-down are affected as can be seen from this figure. Increased sheet thickness has an interesting effect on surface temperature. Fig. 9 shows the impact of changing sheet thickness on the surface temperature. Beyond a certain value of the thickness, the sheet is insensitive and the surface temperatures profiles do not change.

Fig 10 shows corresponding temperature fields in two dimensions (i.e. the MD-ZD planes). Fig. 11 shows the surface temperature rise of a two-layered sheet consisting of a base sheet with a coating layer on top in comparison to the same sheet consisting of only the base layer without the coating. The surface temperature of the coated sheet rises and cools rapidly as compared to the base sheet. The higher thermal conductivity and density of the coated sheet are responsible for this behavior. The corresponding temperature fields within the sheet show the clear asymmetry caused by the coating. Increased thermal diffusivities result in deeper penetration of the temperature pulses into the sheets and also higher retention times for the thermal energy. The thermal response is also dependent on sheet thickness for small thicknesses.

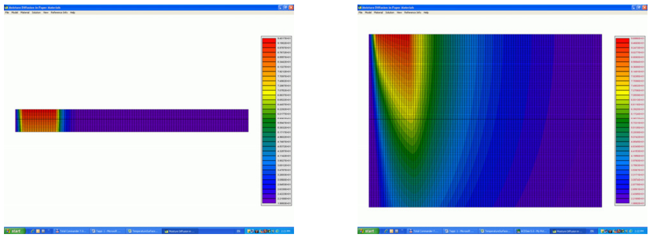

Fig. 10. Temperature distributions in paper sheets with 0.002 cm and 0.015 cm thicknesses

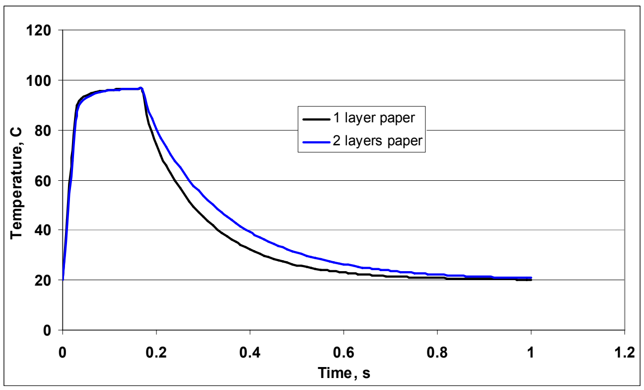

Fig. 11. Coating influence on surface temperature

EXPERIMENTAL PROCEDURE

A commercial copier, the Xerox Docutech 6180 was instrumented with four temperature sensors connected to two computers through data acquisition systems. Two sensors were inserted in the cabinet at different locations near the paper path and close to the fuser roll. An infra-red sensor connected to a T type thermocouple was used to sense the temperature at the surface of the paper sheet as it came out of the fuser section. A Flugt IR thermometer was mounted separately and targeted at the surface of the pressure backing roll using a laser ranging sensor. This was connected to a separate computer and data of the surface temperature of the backing roll was acquired. Fig 12 shows a picture of the internal of the copier with the sensors attached. Fig 13 is a schematic showing the locations of the sensors. Table 2 shows the characteristics of the paper sheets used for the test. These were commercially available copy paper and were identified as samples 1 through 4.

EXPERIMENTAL RESULTS AND COMPARISON OF MODEL PREDICTIONS

Fig 14 shows the four temperatures measured by the sensors for paper sample 1. The copier was run for 1000 copies to allow a reasonable steady state to be attained. The paper was a standard copy paper with BW of 72 GSM (20 lb/3000 sq ft ream). Other properties are as listed in Table 2. It took approximately 500 copies for the temperature of the sheet surface to reach steady state. The ambient temperatures were constant at 25 C. The paper surface was at 90 C and the pressure roll was at 65 C. The pressure roll surface temperature decreased with time until it reached a steady state. During the heat up period when no copying occurs, the pressure roll and the fuser roll are in (imperfect) thermal contact which results in heating of the pressure roll to an initially high temperature. The pressure roll temperature decreases with time as it loses heat to the paper sheets.

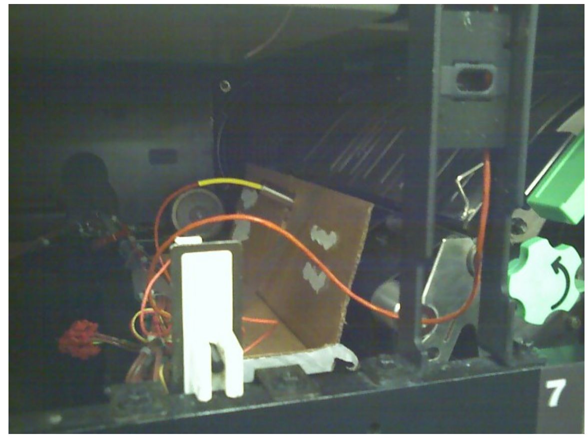

Fig 12. Picture of the interior of Xerox Docutech 6180 with sensors placed in the paper path. Sketch of the various sensors is shown below.

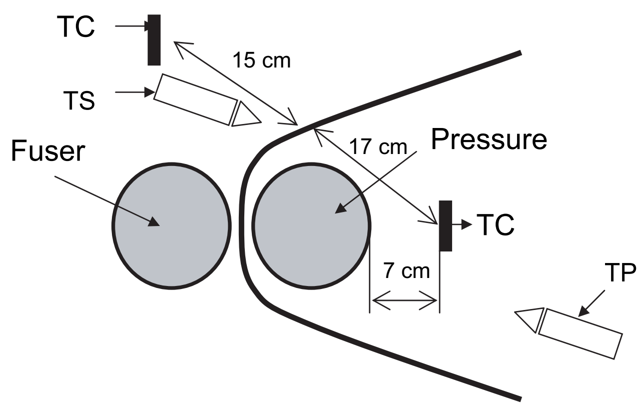

Fig 13. TC1 – Thermocouple (T type) for measuring ambient environmental temperature, near paper surface. TC2 – Thermocouple (T type) for measuring ambient temperature near pressure roll. TS – IR sensor with K type connector for paper surface after fuser (approx. 8 cm). TP – IR camera sensor with laser ranging. Temperature of fuser roll.

Table 2. Properties of paper sheets used in experiments.

	Paper 1	Paper 2	Paper 3	Paper 4	Paper 5	Paper 6
Paper ID	Uncoated 1, 20 lb	Color Copy Cover 60lb	Color Copy Cover 80lb	Glossy cover 80lb	Uncoated 2, 20 lb	Uncoated 3, 24 lb
Basis Weight, g/m^2	75.6	165.0	222.0	212.0	75.7	88.6
Caliper, µm	98.8	173.2	220.2	198.6	94.3	113.3
Density, kg/m^3	765.1	951.9	1005.8	1067.8	803.4	784.4
Filler Content, %	20.7	27.8	26.9	21.6		
Conductivity, W/cm/K	0.0011	0.00175	0.0022	0.00245	0.000968	0.000972
Specific Heat, J/g/k	1.4	1.1	1.0	1.0	1.2	1.2
Press Roll Temperature, C	72.7	53.3	51.4	46.5	77.6	71.1

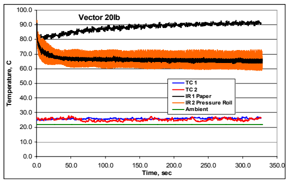

Fig 14. Temperatures of various sensors with machine running paper 1. Paper surface (IR 1) is the highest temperature. Copier achieves steady state after about 700 copies. Run for 1000 copies. Ambient, TC1 and TC2 are approximately the same. Copier speed is 180 ppm.

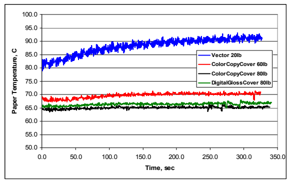

Fig 15. Temperature of paper surface for different copy paper grades. Heavier paper grades (higher BW) result in smaller surface temperature. The paper 4 sheet has higher surface temperature probably due to higher thermal conductivity (higher thermal diffusivity also).

Fig 15 shows the paper surface temperature for the paper samples 1 through 4. The surface temperature was the highest for sample 1 which had the smallest caliper, basis weight and density. These sheets tend to have the least thermal capacity and can heat up more rapidly than heavier grades. Samples 2 and 3 are cover copy paper with higher basis weights. The surface temperatures are significantly lower in these cases. Sample 4 is a glossy copy paper with high filler level which cause higher thermal conductivity and sheet density although the specific heat tends to be lower [6]. The sheet surface temperature is higher than its counterpart cover stock (80 lb). The pressure roll temperatures decrease with each of these sheets as shown in Fig 16. The decreased temperature is due to the higher sheet thermal capacities as well as higher sheet thicknesses. Both these serve to lower the bottom surface temperature of the paper sheets as they travel through the fuser section. Fig 17 summarizes all the experimental measurements for the temperatures for the paper sheets. The fluctuations are caused by the gaps between the sheets during their travel as well as the modulation of the temperature measurements with the response characteristics of the thermometers (IR & thermocouples). By comparison, we observe that the magnitude of the fluctuations decreases with increased thermal mass and conductivity of the sheets. This is expected from the transient thermal response of paper sheets.

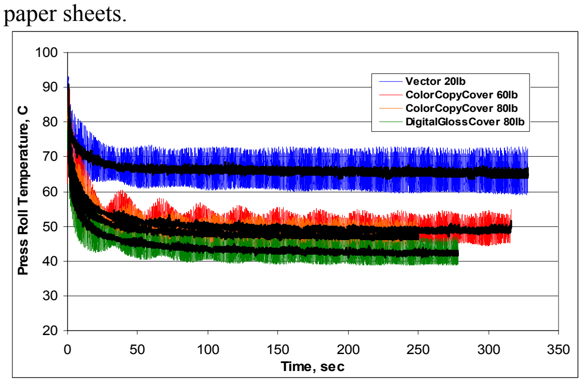

Fig 16. Press roll temperature for different paper sheets. Press roll temperature also decreases with increased BW. However, paper 4 shows the smallest temperature whereas paper 3 is higher. This may be because the thermal pulse in the coated paper gets dissipated in the top layer and does not penetrate deep enough into the base sheet. The magnitude of oscillations for paper 1 are highest. Magnitude of oscillations decrease with BW.

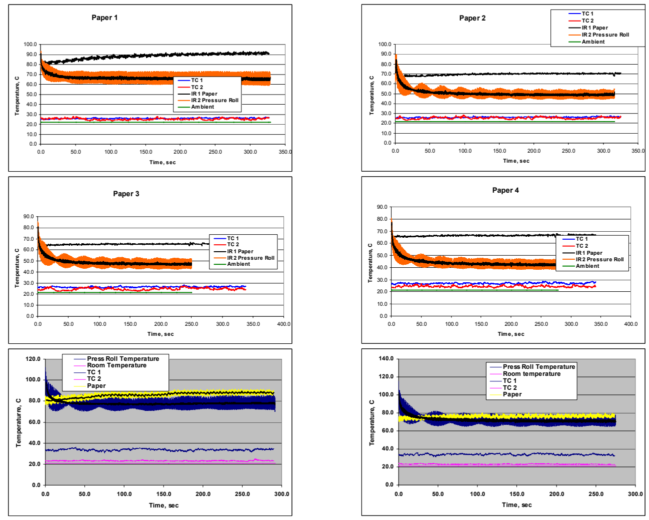

Fig 17. Temperatures within copier for each paper grade.

Fig 18 shows the average sheet temperature on the top surface of the paper as measured by the sensor and also the corresponding average calculated by the mathematical model. A very close correspondence between the surface temperatures was obtained.

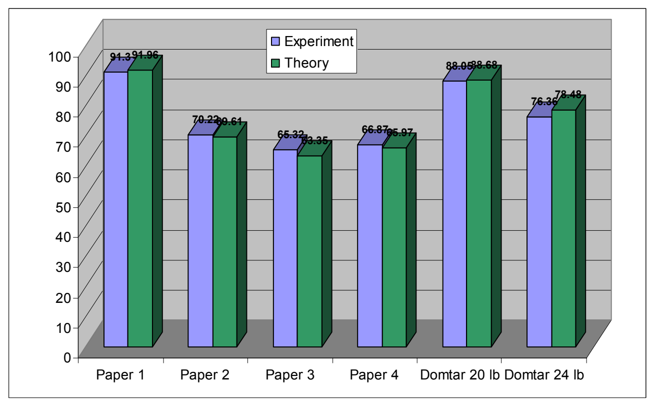

Fig 18. Average temperature of paper on sheet surface – comparison of model predictions with experimental results.

DISCUSSION AND CONCLUSIONS

The thermal response of the sheets can be seen to be strongly impacted by the sheet properties. In particular, the sheet basis weight, density, thermal conductivity and heat capacity are critical in determining this response. Since the thermal properties are dependent on sheet moisture content, the response would also be sensitive to moisture content although this was not directly investigated in this work.

Author Biography

S. Lavrykov received his BS and MS in Mechanical Engineering from the Technical University of Ukraine, Kiev, Ukraine. He has been a research scientist at the Empire State Paper Research Institute since 2001.

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K. M. Singh received his BS in Chemical Engineering from the Indian Institute of Technology, Delhi, India and MS and Ph D in Paper Science and Engineering from SUNY Environmental Science and Forestry in Syracuse, NY, in 1988. He is currently a senior research scientist with International Paper Co., in Loveland OH

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