QUANTITATIVE DETERMINATION OF IN-PLANE MOISTURE DISTRIBUTION IN PAPER BY INFRARED THERMOGRAPHY

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ABSTRACT

The objective of this study was to determine the correlation between surface temperature distribution measured by an infrared thermography technique and moisture content distribution determined by a gravimetric method. Paper sheets were constrained such that diffusion would predominantly be in one in-plane direction. Both measurements were taken as a function of time for a sorption process. The results indicated that the temperature fields measured by the thermography tool were in general, linearly related to the percent moisture content measured by the gravimetric method. The thermal imaging method provides a useful technique to quantify in-plane moisture distribution in paper.

INTRODUCTION

Gravimetric determination of in-plane moisture distribution in paper is slow, laborious, and possibly inaccurate depending on the instruments used. A faster, full-field measurement of the moisture content is desirable. With such method one could investigate in-plane diffusion characteristics of paper. In-plane diffusion of moisture is an important aspect for understanding moisture distribution in paper rolls, stacked sheets, and products such as polycoated board. One possible technique is to utilize infrared cameras to detect the moisture distribution. The most common application of infrared cameras in the paper industry has been in the areas of troubleshooting, diagnostics, and condition monitoring [1-3]. Charles [1] applied a high-speed line-scanned infrared imaging technique to perform diagnostics on a Yankee dryer used in the tissue/towel-making process and on a size press in the newsprint machine. He also reported the use of an infrared camera in detection of cockle in light-weight coated sheets. Location of a surface depression at a pressure roll of the Yankee dryer produced an inadequate pressing that appeared as a cold/wet spot in the thermographs, and the problem was solved by repairing the

low area. That study also compared application of the full-frame with that of the line-scanned infrared imaging. Kiiskinen et al. [2] also used an infrared camera to capture images of cockles in newsprint and fine paper samples. With this technique, they also observed development of differences in moisture content of paper samples during the drying process.

During the papermaking process, after the forming and press sections, the last stage of water removal from paper occurs in the dryers, where moisture is essentially removed by evaporation and vapor transport. Several phenomena including moisture movement by diffusion and local condensation may occur during drying [4]. These are energy-intensive processes, but their mechanism is not well understood. The method and rate of drying have an impact on formation of cockle and localized surface non-uniformities in low basis weight papers. Development of an in-plane inhomogeniety in moisture content can result in a difference in potential for hygroexpansion in localized regions, which may result in local buckling or cockle in paper [5]. As long as inhomogenieties in formation and water removal are present, these surface nonuniformities will be produced in the dryer section. Additional studies are needed to quantify the influence of drying methods on surface conditions of paper. It is known that rapid temperature changes near the glass transition temperature in viscoelastic materials can result in development of stresses within these materials. Under some restrained conditions, these stresses may produce relatively large out-of-plane deformation in these materials [6]. Considering the fact that paper is a viscoelastic material, temperature changes at the dryer section may result in development of thermal stresses that are responsible for initiation of surface nonuniformities. A full-field and on-line measurement of moisture content at the dryer section can provide information on these moisture nonuniformities along the cross machine and machine directions. In paper materials, any localized surface nonuniformity, such as cockle, cracks, or wear, influence infrared radiation characteristics of the surface and result in fluctuation of radiation intensity which may manifest itself as local temperature nonuniformity (e.g., hot or cold spots) in thermographs. Therefore, on-line recording of thermal images and evaluation of these temperature non-uniformities in paper surfaces could provide valuable information about the surface conditions and the physical and mechanical characteristics of the web.

An interesting work in paper mechanics was conducted by Yamauchi and Murakami [7], who applied infrared thermography to study fracture patterns and crack propagation in notched handsheets subjected to tensile loading. The transient tensile stresses developed within paper samples resulted in local deformations. These deformations produced temperature nonuniformities in infrared thermographs. Infrared imaging techniques can also be employed for identification of substances without the necessity of the labor and time required in conventional methods and is especially suitable for detecting the presence of stickies in recycled paper [8]. Infrared thermography has also been used to generate surface temperature maps of veneer and wood flakes during drying [9]. The thermal imaging technique is currently being used to evaluate performance of a press roll in a paper machine producing fine papers at a speed of 732 m/min [10]. In that study, a nonuniform temperature distribution along the cross machine direction (CD) in the sheet passing from the press roll which corresponds to a nonuniform moisture distribution, revealed a sign of nonuniform pressure distribution induced on the paper web by the press roll.

After the paper is produced, the moisture content will change as it is introduced to new environments. A previous study [11] reports that in-plane moisture diffusion is faster than that of through-plane diffusion, however, only limited qualitative results related to this finding are

available. Magnetic Resonance Imaging (MRI) has proven to be a very useful technique in detecting liquid-phase molecules in various materials. Application of MRI to characterize moisture diffusion in pulp and paper has been reported in previous studies [12-16]. However, gas-phase molecules of water occur at concentrations which may be too low to be detected by the MRI technique [12]. Also, because of a relatively small diameter of the MRI probe, the paper sample that can be used in this technique is generally quite limited in shape and dimensions (e.g., a circular sample approximately 2 cm in diameter).

This study examines an alternative method to measure in-plane distribution and movement of water measurement and detection of moisture in paper by thermography. This is a nondestructive and noncontact method and, compared to the current laboratory methods, provides results in a much shorter time frame.

PRINCIPLE OF THERMOGRAPHY

Radiation, which is emitted by all objects, can be used to monitor and measure the surface temperatures of the objects. At relatively low temperatures, the predominant type of radiation emitted is the infrared radiation which is invisible to the human eye. At higher temperatures, the intensity of the infrared radiation increases significantly. Therefore, variation in surface temperature results in variation in the infrared intensity [17]. An infrared camera detects the radiation intensity of an object not the temperature and the detected intensity is influenced by the object surface emissivity, atmospheric absorption, ambient temperature, and other radiative heat transfer properties of the object and environment. An infrared camera can be used to register and display different infrared intensities as different colors, which are called thermographs. Thermography is an important diagnostic tool in various industries, including medicine, defense, space research, and fire protection.

The spectral distribution of the radiation $I_{\lambda,b}$ from a blackbody was described by Max Planck according to the following equation:

$$I_{\lambda,b} = 2\pi hc^2 / \{ \lambda^5 [\exp(hc/\lambda kT)-1]\} \quad (1)$$

Where h = Planck's constant=6.625 x 10^{-27} [erg.s],
c = velocity of light=2.998 x 10^{10} [cm/s],
k = Boltzmann's constant = 1.380 x 10^{-16} [erg/K],
λ = wavelength of emitted radiation [cm]
t = temperature of blackbody [K],
and subscript b denotes blackbody.

A blackbody absorbs all incident radiation of any wavelength and it re-emits that radiation uniformly in all directions. In the case of real objects whose absorbency is limited, only a part of the energy will be radiated out from the surface. This fraction of the blackbody spectral radiance is given by the surface emissivity (ε). Under this condition, equation (1) becomes:

$$I_\lambda = \varepsilon I_{\lambda,b} \quad (2)$$

The IR scanner used in this study is a short-wavelength scanner and only detects photon radiation with wavelengths in the 2 to 5.4 μm ranges that allows temperature to be the only variable**.** The paper samples analyzed in this study are considered to be graybodies and not blackbody emitters. The spectral properties of the samples consist of the absorptivity (α), emissivity (ε), reflectivity (ρ), and the transmittance (τ). These factors all must be taken into consideration when determining the temperature of a gray object. For opaque objects (τ=0), Kirchhoff's law relates the emissivity (ε) of the surface patch to the reflectivity (ρ). For an incident isotropic radiation, we can write:

$$\varepsilon = 1 - \rho \qquad (3)$$

Kirchhoff's law states: $\varepsilon = \alpha$; therefore, the object reflectivity can be determined from the emissivity.

EXPERIMENTAL PROCEDURE

Samples from commercial paperboards with basis weights of up to 880 g/m^2 were cut into 4"x4" (10.16x10.16cm) squares using a cutting die. The square samples were dried overnight inside an oven at 110°C. The samples were then taken out of the oven, placed between two rigid and flat teflon plates (4"x4" square) then covered by thin plastic foil and teflon tape such that only the two opposite edges of the samples were exposed to moisture (**Figure 1**). The other two edges and the top and bottom surface areas of the samples were completely insulated such that no moisture could enter or exit from those surfaces. Six samples were prepared in this manner and after the samples were cooled to 22°C they were placed inside a high-humidity room with a set-point temperature and humidity of 22°C and 95%, respectively.

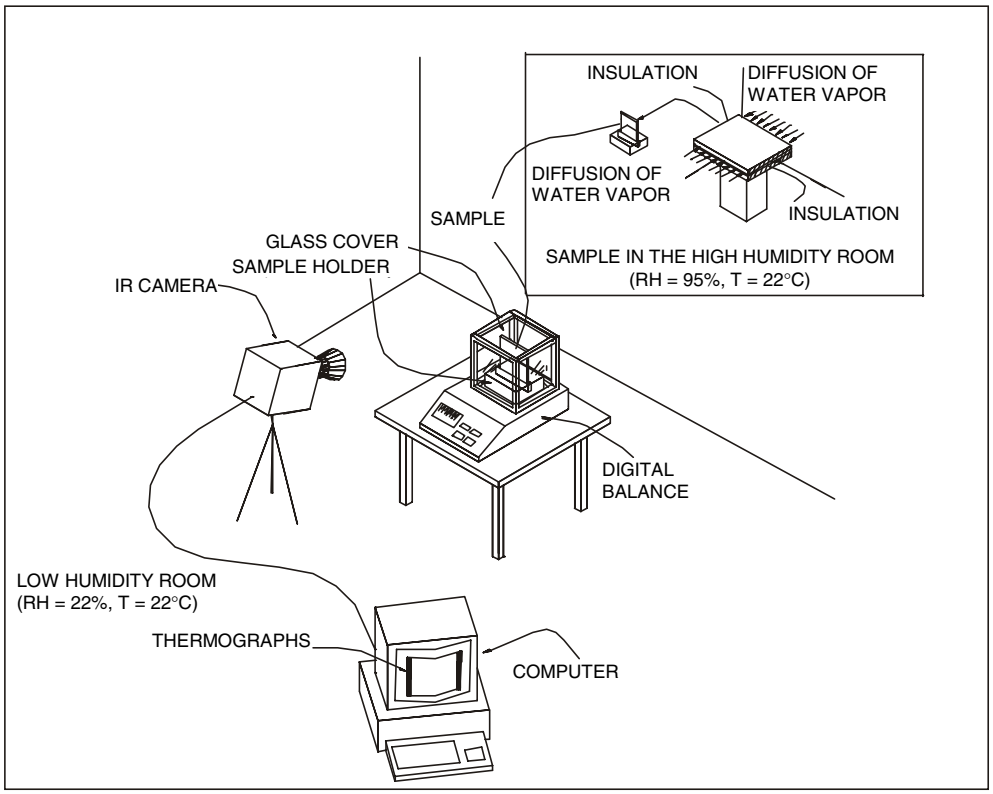

Figure 1. Sample subjected to an in-plane diffusion in a high-humidity room, and the test apparatus in a low-humidity room.

After 30 min, one of the samples was placed inside a sealed plastic container and taken to a low-humidity room (20% RH, 22°C). After removing the covers, the sample was immediately placed on a glass-covered balance located in front of the infrared camera. The surface thermographs and sample's weight were recorded simultaneously using a data acquisition system (Figure 1). Several images were captured from each sample. Then slices of ¼" (6.3 mm) in width from the samples (½" or 12.7mm slice for samples with longer exposure time) were cut perpendicular to the direction of moisture sorption. The slices were weighed and placed inside an oven set at 110°C to measure moisture content of each slice by the gravimetric method.

Each of the remaining samples was exposed to the 95% relative humidity for a different amount of time up to 48 hours, and surface thermographs and moisture content were obtained in the manner described above. The thermal images were recorded using the AGEMA 900 SW/TE system [18]. Mean temperature value corresponding to each slice was determined and an expression for moisture content as a function of temperature was generated.

MECHANISM RESPONSIBLE FOR DEVELOPMENT OF THERMOGRAPHS

In this study, the sheets were initially placed at 95% RH, then at a given time brought back to a condition of 20% RH and the same temperature as the initial condition (22°C); then the thermal images were taken. Under the condition of 20% RH, the partial pressure of the air moisture in the measuring environment would be smaller than that of the air near the sample. A small desorption of moisture occurred near the surface of the sample that resulted in a small temperature reduction in a localized surface area. This localized cooling was due to the fact that desorption of moisture is endothermic in nature. In other words, the reduction of sample surface temperature can be related to the latent heat of vaporization of free water molecules in the paper, which produce a localized evaporative cooling at the sample's surface. The rate of evaporation is influenced by vapor pressure at the sample's surface. Increasing vapor pressure will result in a greater evaporation [4] and thus an increase in local evaporative cooling.

Regions that are higher in moisture content are associated with a greater reduction of surface temperature (e.g., darker areas in the thermographs). A small variation in moisture content at the sample's surface will result in only a very small temperature gradient; however, the infrared camera can easily detect this temperature variation. The energy required to sustain the evaporation comes from the internal energy of the liquid water in the paper which results in a temperature reduction. This temperature reduction due to the evaporative cooling process can be determined from the following equation [19]:

$$T_\infty - T_S = \frac{M_a h_{fg}}{R \rho C_P Le^{2/3}} \left[\frac{1}{\overline{T}} (\phi P_{v,sat}(m_r, T_S) - P_{v,\infty})\right] \quad (4)$$

where, $\overline{T} = (T_\infty + T_s)/2$ in which T_∞ and T_s are the ambient and the surface temperatures in Kelvin (K) scale, respectively, M_a is the molecular weight of water, h_{fg} is the latent heat of vaporization, R is the ideal gas constant for air, ρ and Cp are the density and constant-pressure specific heat of air, $Le = \alpha / D$ in which α is the thermal diffusivity of air and D is the diffusion coefficient of vapor in air, ϕ is a pressure ratio [$\phi = P_v(T, m_r)/P_{v,sat}(T_s)$] as described in a study by

Prahl [20], $P_{v,sat}$ (m_r,T_s) is the saturated vapor pressure evaluated at the surface temperature, and $P_{v,\infty}$, is the vapor pressure of water in the environment away from the paper sample. In this relation, it is assumed that the paper sample is under a steady-state condition in which heat transfer from the sample interior or balance tray is negligible. If evaporation is occurring in a dry room, then $P_{v,\infty} = 0$, and equation (4) can be simplified to:

$$T_s^2 - T_\infty T_s + B = 0 \qquad (5)$$

where T_s and T_∞ are in Kelvin temperature and B is obtained from the following equation:

$$B = \frac{M_a h_{fg} P_{v,sat}}{R \rho C_p Le^{2/3}} \qquad (6)$$

However, it should be noted that under this condition B is still a function of surface temperature. Thus, despite the fact that equation (5) appears to be much simpler than equation (4), it still has to be solved by an iterative scheme.

RESULTS AND DISCUSSION

Shown in **Figure 2** is a plot of percent moisture content as measured by the gravimetric method versus distance along the sample width in the direction of moisture diffusion at six different diffusion times for the six paper samples subjected to in-plane diffusion. Because of symmetric boundary conditions, moisture contents for only half of the sample width is plotted. The horizontal axis corresponds to distance from the exposed edge of the sample (origin) to the midpoint of each strip. For the samples with 30-min and 120-min exposure times, the strips were cut ¼" (6.3 mm) in width, and for other samples, the width of each strip was ½" (12.7 mm). As expected, the gradient of moisture is greatest near the edge of the sheet. For exposure time of up to 120 min, the maximum penetration was approximately 22 mm. Even after 24 hours exposure to 95% RH, there was a relatively large in-plane moisture gradient in the sample.

Figure 3 shows the thermographs of the six samples at each time interval. Regions at higher temperature (lower moisture content) are represented by lighter colors and regions at lower temperature (greater moisture content) are shown by darker colors. These thermographs show that after three hours (180 min), except for a thin region near the exposed edges, the remaining surface areas of the sample are at a relatively uniform temperature. This indicates that the diffusion process was very slow and during this period moisture penetrated only into a small region in the sample.

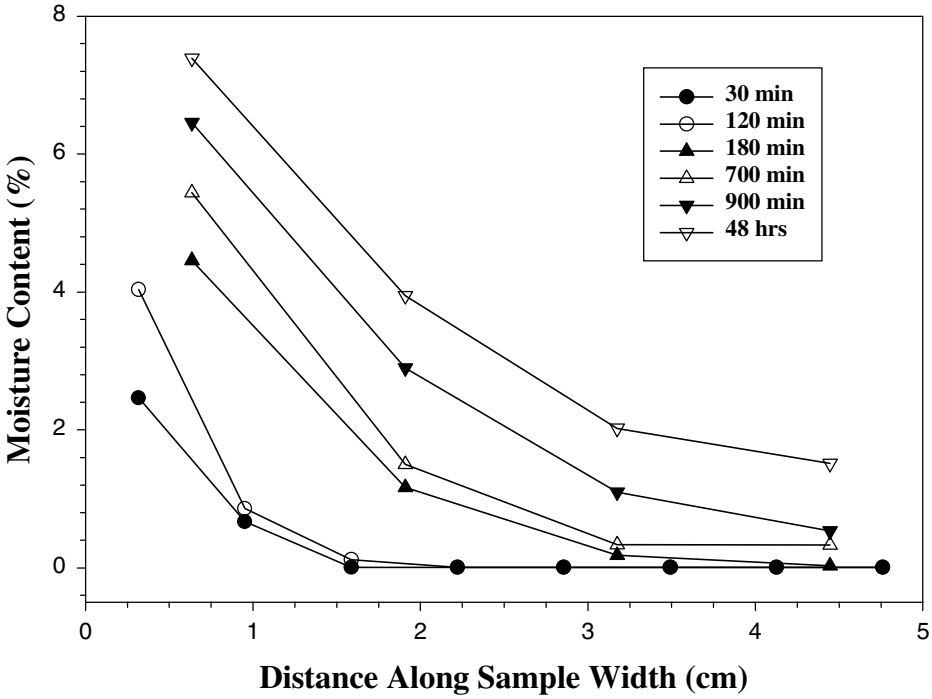

Figure 2. Percent moisture contents versus distance at various diffusion times.

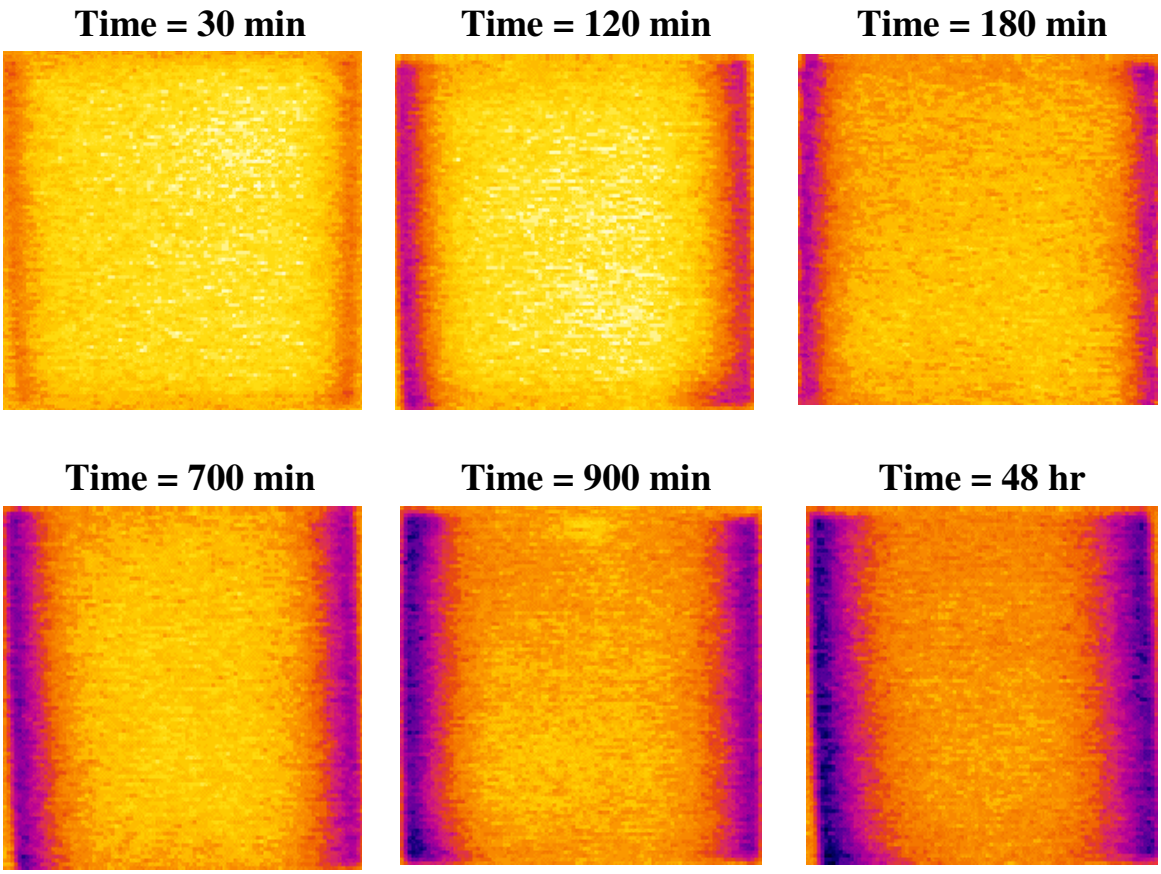

Figure 3. Thermographs of six samples at each diffusion time.

Shown in **Figure 4** are plots of the temperature determined from the thermographs as a function of distance along the sample width. Each point on this graph corresponds to the average surface temperature of all points, which are at the same distance from the exposed edge of the sample. For each diffusion time, the surface temperature increases with distance from the edge of the sample. **Figure 5** shows the percent moisture content of the slices as measured by the gravimetric method as a function of surface temperature for each corresponding slice determined from the recorded thermographs. For each diffusion condition, the moisture content value of each slice is platted against the mean temperature of the corresponding slice. Further analysis of data indicates that the temperature for one of the data points corresponding to the 180-min diffusion time (shown by a diamond symbol) apparently was an anomaly. This point corresponds to the edge slice for this sample. Figure 4 also indicates that near this region, there was an overlap between the surface temperatures of 120-min and 180-min cases due to some experimental error. Therefore, this point was excluded from the analysis of linear regression. The R^2 value for the best fitted line was 0.94 and the equation of the line is shown on the graph (Figure 5). It should be emphasized that this calibration curve is generated based on measurement of surface temperatures and moisture contents in only one sample for each diffusion time. Therefore, the effect of variation within samples, influence of irregularities in sample's emissivity, and environmental changes are not considered. In order to generate a more precise correlation between the moisture content and the surface temperature, experiments should be conducted using several samples in each group. Shown in **Figure 6** is the average moisture content as measured by the gravimetric and thermal imaging methods as a function of square root of time ($t^{1/2}$). For the ($t^{1/2}$) values of 8 to 18 $min^{1/2}$, the plots for both methods approximately follow a straight line.

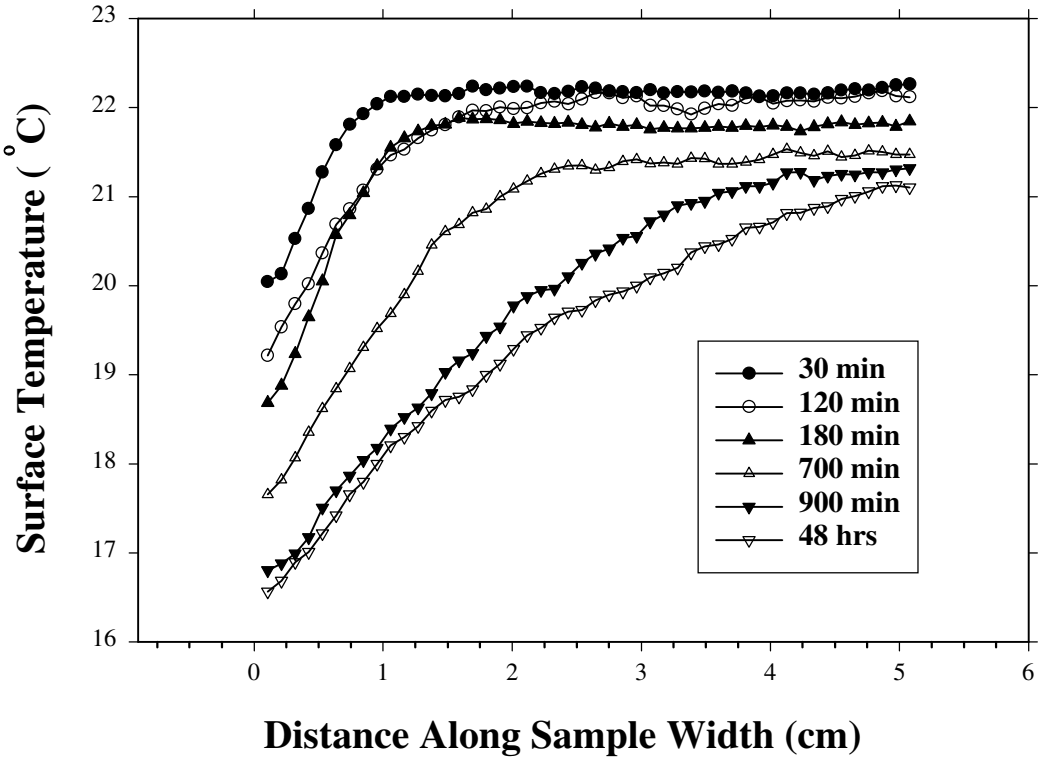

Figure 4. Surface temperature distribution at each diffusion time as determined from the infrared thermographs.

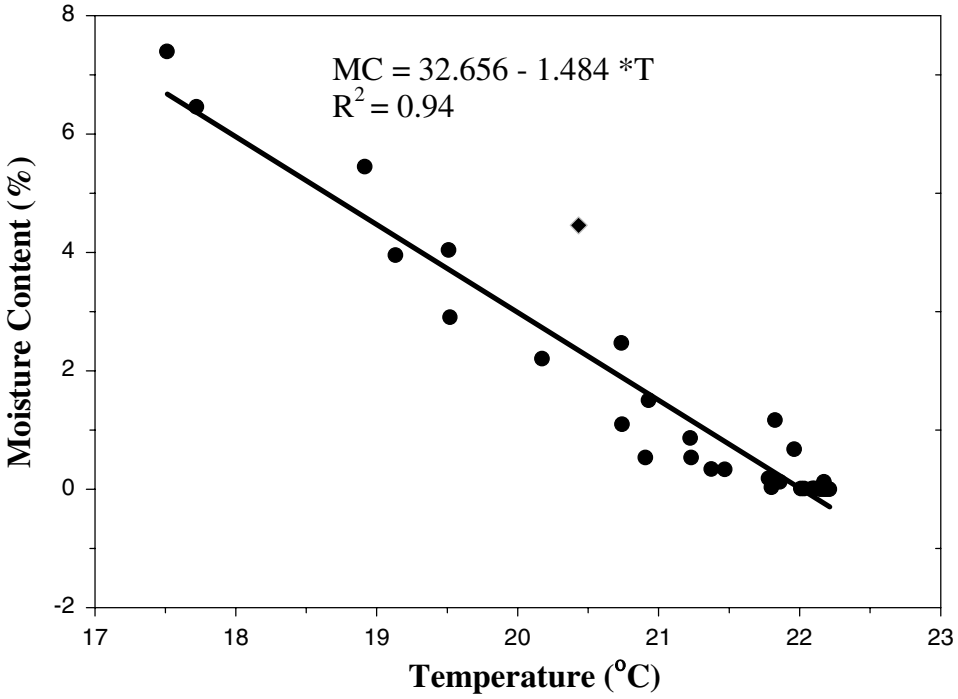

Figure 5. Percent moisture contents as a function of surface temperature.

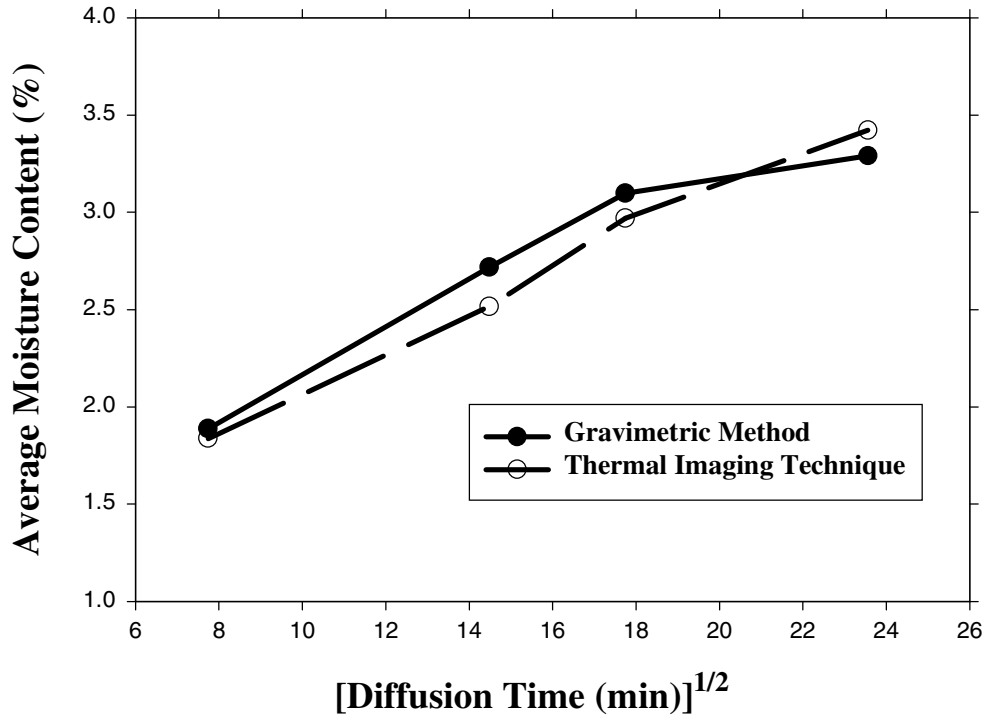

Figure 6. Percent moisture contents as a function of square root of the diffusion time.

It is important that measurement of moisture in paper be accurate and desirable that it be a full-field measurement in real time. An infrared system that is generally used by the paper industry as a diagnostic tool or temperature monitoring device, if employed under suitable environmental temperature and moisture conditions, can also be used to detect moisture content in paper materials. Although the collected infrared signals are only associated with the surface of the paper, under conditions in which the moisture gradient through the thickness of the paper is not significant the signals can provide a quantitative measure of moisture content corresponding to the location of interest. As indicated, comparison of the four thermographs captured within 30 seconds showed no significant variation in surface temperatures. This indicates that for the moisture exposure time and other conditions of this study, in general, the moisture gradient through the thickness of the sample had a negligible influence on the measured surface temperatures.

CONCLUSIONS

This study indicated that in general, the surface temperature values measured from thermography varied linearly with the percent moisture contents determined from the gravimetric method. Thus, the thermal imaging method provides a useful technique to quantify in-plane moisture distribution and diffusion in paper sheets. Application of Infrared Thermography at the dryer section and incorporation of the measured surface temperatures in models that couple computational mechanics (e.g., finite element stress analysis) with a heat and mass transfer model [e.g., equation (4)] can provide insight for better understanding of mechanism responsible for development of moisture nonuniformities in paper. Future studies with infrared thermography should also determine the influence of fiber orientation on the in-plane diffusion of moisture in paper materials.

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