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INFRARED THERMOGRAPHY AS A TOOL FOR MEASURING IN-PLANE MOISTURE DISTRIBUTION IN PAPER

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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 linearly related to the percent moisture content measured by the gravimetric method and the corresponding correlation coefficient of the linear regression was relatively large (R^2 = 0.97). The thermal imaging method could provide a useful technique to quantify in-plane moisture distribution in a paper web during papermaking and diffusion of water vapor in paper sheets during end-use.

INTRODUCTION

Gravimetric determination of in-plane moisture distribution in paper is slow, laborious, and possibly inaccurate depending on the instruments employed. A faster, full-field measurement of the moisture content is desirable. If such methods could be used, one could easily investigate in-plane diffusion characteristics of paper. In-plane diffusion of moisture is an important aspect for understanding moisture profiles in paper rolls and moisture movement in products such as poly-coated board. In addition, such methods could be employed on-line to measure moisture profiles on a web, provide input for control schemes, and ultimately increase process efficiency, reduce energy cost of drying, and improve product quality. The most common application of infrared cameras in the paper industry has been in the areas of troubleshooting, diagnostics, and condition monitoring [1-3]. Kiiskinen et al [2] 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. In paper materials, any localized surface nonuniformity, such as cockle, defect, crack, or wear, which influence the emissivity or other infrared radiation characteristics of the surface (e.g., heat convection, reflection, etc.) can result in fluctuation of radiation intensity which will 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 surface 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 [4] who applied infrared thermography to study fracture patterns and crack propagation in notched hand sheets subjected to tensile loading. The tensile stresses developed within paper samples resulted in local deformations. These deformations produced temperature nonuniformities in infrared thermographs. A series of thermal images of notched hand sheets under tensile strain were developed. There was a linear relationship between the temperature change in the handsheet and the percent elongation. A temperature increase of 0.4°C was detected for handsheets subjected to 4% elongation of the samples. However, higher local stress concentrations, which occurred in the middle of the plastic range, resulted in a slightly greater temperature variation. Infrared imaging technique 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 [5]. In a more recent study, infrared thermography has been employed to generate surface temperature maps of veneer and wood flakes during drying [6]. 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 [7]. In this study, a non-uniform 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 possible sign of nonuniform pressure distribution induced on the paper web by the press roll.

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 [8]. This is a highly energy demanding process but its mechanism is not well understood. After the paper is produced, the moisture content will change as it is introduced to new environments. A previous study [9] 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. However, gas-phase molecules of water occur at concentrations which may be too low to be detected by the MRI technique [10]. Application of MRI to characterize moisture diffusion in pulp and paper has been reported in previous studies [10-14].

This study examines an alternative approach for measurement and detection of moisture in paper by Thermography. This is a nondestructive and non-contact 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 [15]. The detected intensity depends upon the object surface emissivity, atmospheric absorption, ambient temperature, convective heat transfer, reflection, and whether or not there is any special absorption or radiation effect [3]. 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 medicine. Also, it is widely used in industrial applications and other fields, such as 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:

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

Where h=Planck's constant=6.63 x 10^{-34} [J.s], c= velocity of light = 3 x 10^8 [m/s], k=Boltzmann's constant = 1.381 x 10^{-23} [J/K], λ = wavelength of emitted radiation [μm], T = Temperature of blackbody [K], and subscript b denotes blackbody. 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 utilizing a limited solid angle. This allows temperature to be the only variable. 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:

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

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 relate 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. The AGEMA 900 [16] allows the object emissivity to be specified. The system also compensates for transmission through the atmosphere.

EXPERIMENTAL PROCEDURE

Samples from commercial paper boards with a basis weight of up to 880 g/m^2, which were made from an unbleached softwood kraft pulp, were conditioned at a temperature of 22°C, and a relative humidity (RH) of 50% for at least 24 hours. Then they were cut into 4"x 4" (10.16x10.16 cm) 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"x 4" square) then covered by thin plastic foil and teflon tapes such that only the two opposite edges of the samples were exposed to moisture (Fig. 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 placed inside a high humidity room with a set-point temperature and humidity of 22°C and 95%, respectively.

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. Simultaneously, the surface thermographs and sample's weight were recorded using a data acquisition system (Fig. 1). Then slices of ¼" (6.3 mm) in width from the samples (½" or 12.7 mm 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 gravimetric method.

Each of the remaining samples was exposed to the 95% relative humidity for a different amount of time, and surface thermographs and moisture content were obtained in the manner just described. The thermal images were recorded using the AGEMA 900 SW/TE system. This system includes an IR scanner equipped with a 40° FOV IR lens and a high-speed system controller [16]. The results were analyzed with the IRWin Research 2.01 software. Mean temperature value corresponding to each slice was determined and an expression for moisture content as a function of temperature was generated. To determine effect of fiber orientation on moisture sorption, some samples were insulated from moisture diffusion except from two opposing edges as before. The samples were insulated either parallel to the direction of fiber orientation (machine direction, MD) or perpendicular to MD (cross machine direction, CD). Thermal images were generated in a similar manner.

RESULTS AND DISCUSSION

Shown in Fig. 2 is a plot of percent moisture content as measured by the gravimetric method versus distance along the sample width at six different diffusion times for the six paper samples subjected to an in-plane diffusion. Water vapor diffused into the samples only from two opposite edges under the condition of 95% relative humidity (RH) for a period of 30 min to 48 hours. Because of symmetric boundary conditions, moisture contents for only half of the samples are plotted. The horizontal axis corresponds to distance from the mid-point of each strip to the exposed edge of the sample. 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 2 cm. Even after 24 hours exposure to 95% RH, there was a relatively large in-plane moisture gradient in the sample which indicates that the water vapor diffusion process in paper is quite slow.

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 two hours (120 min), except for a thin region near the exposed edges, the remaining surface areas of the sample are at a 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.

Shown in Fig. 4 are plots of the temperature values determined from the thermographs as a function of distance along the sample width which are shown as pixels. A distance of 10.16 cm (4") is represented by 100 pixels. Shown in Fig. 5 is the percent moisture content of each slice as measured by gravimetric method as a function of surface temperature for each slice determined from the recorded thermographs. The measured values are represented by a linear regression line. The negative slope of the line and the R^2 value of 0.97 indicate that the moisture content and the surface temperature are proportional. The two points that appear further away

from the predicted line were not included in the analysis of regression.

Shown in Fig. 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 follow a straight line for a diffusion process. Considering all samples, it appears that the data from the thermal imaging are closer to straight line than those measured by the gravimetric method. This study indicated that the surface temperature values measured from the thermography varied linearly with the percent moisture contents determined from the gravimetric method. Thus, the thermal imaging method could provide a useful technique to quantify in-plane moisture distribution and diffusion in paper sheets.

In this study, the sheets were initially placed at 90% RH, then at a given time brought back to a condition of 20% RH and at 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, one can relate the reduction of sample surface temperature 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 [8] 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 [17]:

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

where, $\bar{T} = (T_\infty + T_s)/2$ 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 [18], $P_{v,sat}\,(m_r, T_s)$ 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:

$$T_s^2 - T_\infty T_s + B = 0 \tag{5}$$

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

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

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.

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 which 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 for detection of 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 fact, the moisture gradient through the thickness of the sample had a negligible influence on the measured surface temperatures.

It is known that 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 [19]. 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 direction. As long as inhomogenieties in formation and water removal are present, these surface non-uniformities 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 transient and residual stresses within these materials. Under some restrained conditions, these stresses may produce relatively large out-of-plane deformation in these materials [20]. Considering the fact that paper is a viscoelastic material, temperature changes at the dryer section may result in development of transient and residual thermal stresses that are responsible for initiation of surface nonuniformities. 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 these phenomena.

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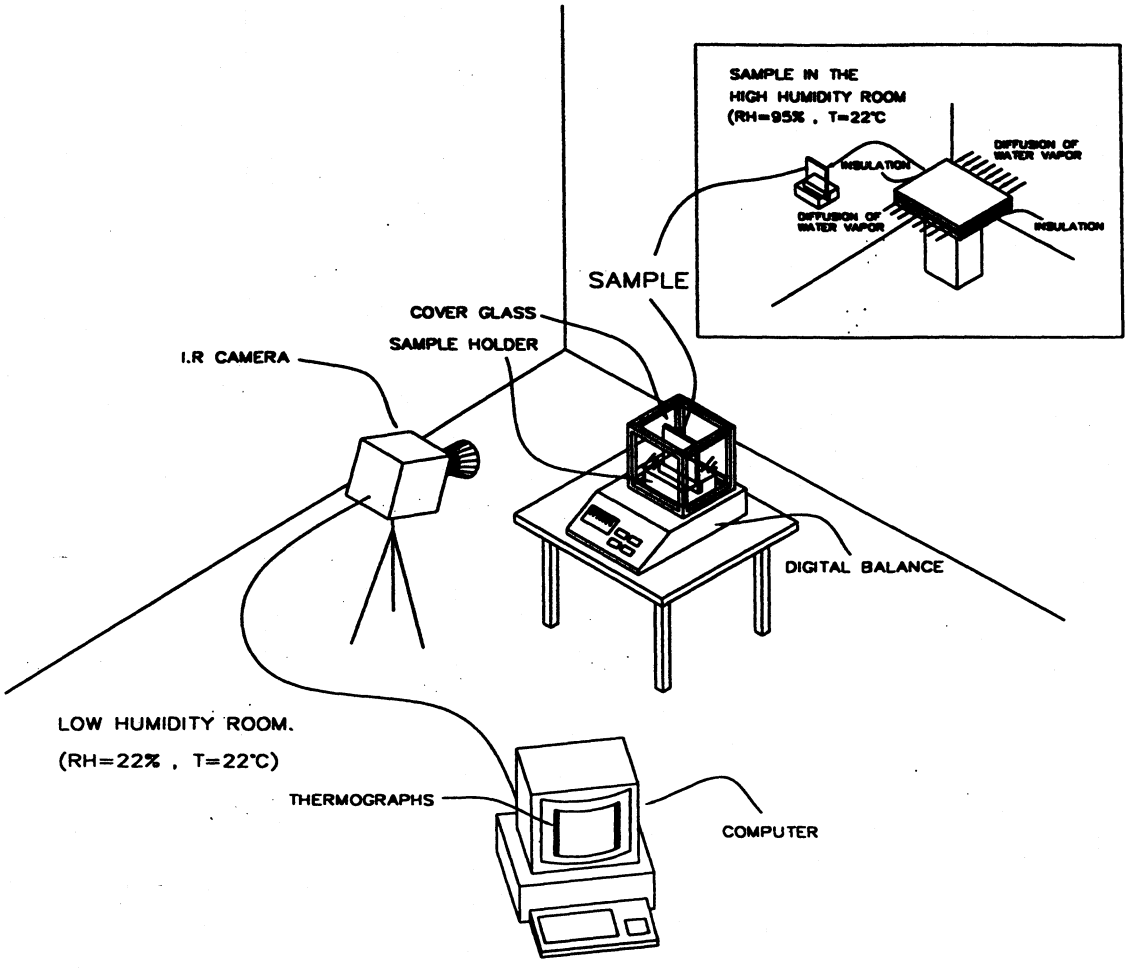

Fig. 1- Sample subjected to an in-plane diffusion in a high-humidity room, and the test Apparatus in a low-humidity room.

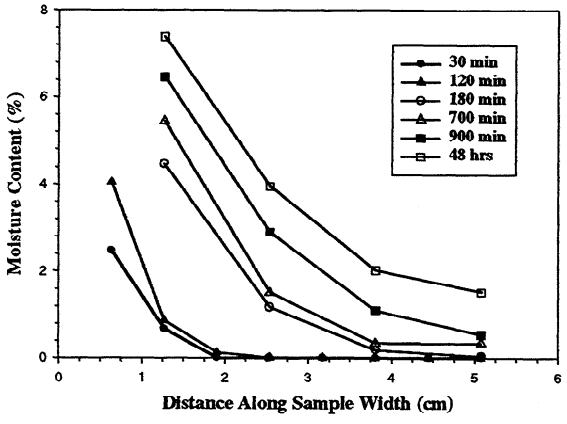

Fig. 2- Percent moisture contents versus distance at various diffusion times.

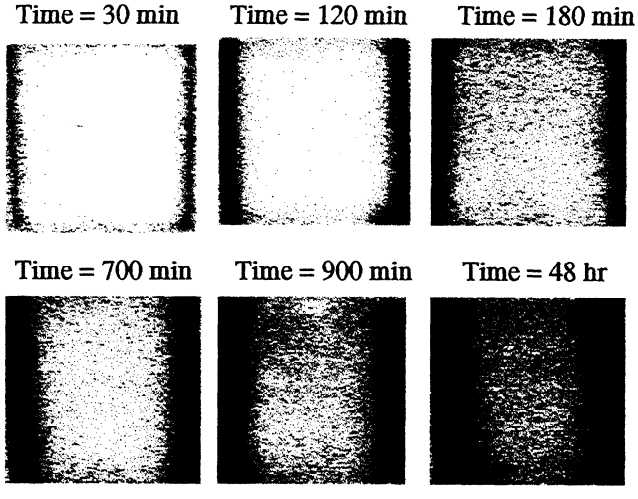

Fig. 3- Thermographs of six samples at each diffusion time.

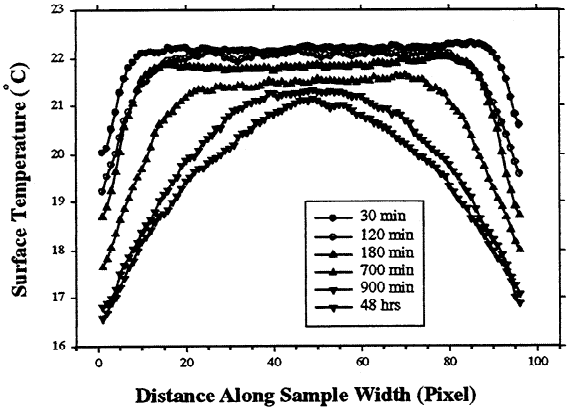

Fig. 4- Surface temperature distribution at each diffusion time as determined from the infrared thermographs

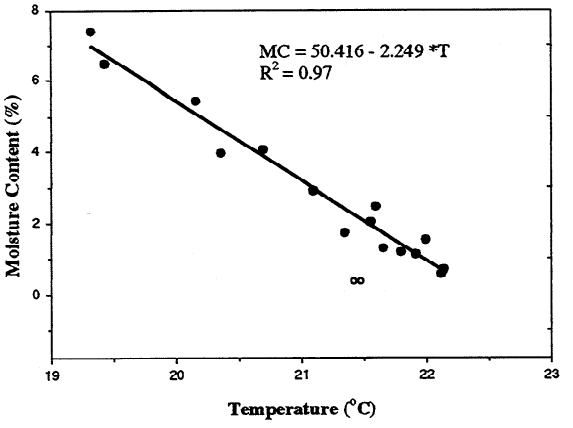

Fig. 5- Percent moisture contents as a function of surface temperature.

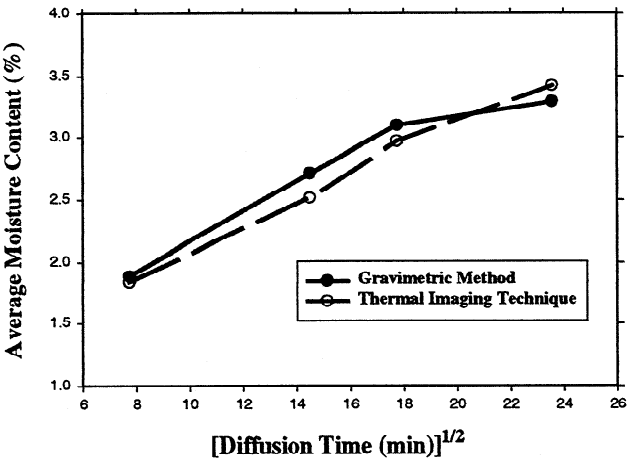

Fig. 6- Percent moisture contents as a function of square root of the diffusion time.