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Lumber moisture evaluation by a reflective cavity photothermal technique

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Résumé. — Les méthodes photothermiques constituent une approche pratique pour le contrôle non destructif de la qualité des matériaux industriels car elles sont rapides et non intrusives. Une de ces applications concerne la mesure de l'humidité pour le contrôle du procédé de séchage du bois. Cet article décrit une méthode photothermique pour l'évaluation du degré d'humidité dans le bois humide à partir de l'évolution thermique de la surface sous irradiation laser. On montre ici que l'effusivité thermique est beaucoup plus sensible que la diffusivité thermique aux variations du contenu d'humidité. Une cavité réfléchissante est utilisée afin d'accroître l'absorptivité ainsi que l'émissivité effectives de la surface inspectée de façon à augmenter la fiabilité des mesures. On présente et on discute les résultats obtenus avec une cavité hémisphérique décentrée sur des échantillons en bois à différents contenus d'humidité.

Abstract. — Photothermal methods constitute a convenient approach for the nondestructive quality control of industrial materials because they are rapid and noninvasive. One such application is the monitoring of moisture in unseasoned lumber for drying mill process control. This paper describes a photothermal method for the analysis of moisture in wood by measuring its surface temperature rise under laser radiation. It is shown that this parameter is much more sensitive than thermal diffusivity to moisture content variations. A reflective cavity technique is used to increase both the absorptivity and the emissivity of the inspected surface in order to improve the measurement reliability. Results obtained with an off-center hemispherical cavity on wood samples of different moisture content are presented and discussed.

1. Introduction.

Wood moisture is a parameter of primary importance in the lumber industry. The moisture content of a standing tree, expressed as a percent of water weight relative to the dry-wood weight, ranges from 35 percent in the center (heartwood) of some high-density softwood trees up to about 200 percent in the peripheral growth rings (sapwood) of some light species. Lumber must be seasoned in drying kilns before shipping for a number of reasons, including the requirement for dimensional stability, the elimination of warping, splitting and checking of products in use, the prevention of lumber degradation such as biological stain, decay or insect attack, and the preparation for further processing steps such as gluing and impregnation treatments [1]. Typical moisture content levels of kiln dried wood are in the 5 to 15 percent range.

Properly performed drying procedures [1, 2] are

economically important both in terms of the final wood properties and of the avoidance of excess kiln heating costs. Moisture flow modelling during the drying process has been the subject of a substantial amount of research work in the past [2-4]. General guidelines for the process parameters (temperature history, residence time, air circulation) can be established if the required information is continuously available. This requires a knowledge of the initial moisture content, wood board geometry and fiber orientation, moisture directional diffusion coefficients, lumber stack structure, temperature and air flow distribution inside the kiln as well as ambient temperature and relative humidity. A more empirical approach based on the on- or off-line sensing of the actual lumber moisture during or after drying has generally proved to be more effective for a reliable statistical process control. This assumes that proper on-line moisture sensors are available.

Moisture sensors for solid materials may be based

on either a direct moisture measurement, including successive sample weighing or chemical distillation procedures [5, 6], or an indirect moisture evaluation. The latter approach relies on the measurement of a wood property having a strong correlation with the moisture content. The best known techniques are based on measurements of electrical resistance and dielectric properties [1, 6, 7], microwave attenuation [8-10], response to nuclear radiation [11, 12] and infrared spectroscopy (Ref. [13], Sect. 8.3.2). On-line direct moisture monitoring methods including in-process weighing of the whole or of a selective part of the lumber load, or else the continuous monitoring of air flow and relative humidity differential in the exhaust kiln-circulated air (Ref. [1], pp. 47, 48) have found some application, but they lack precision and require a previous knowledge of the initial average moisture content of the lumber charge. Indirect moisture sensors are more widely used for continuous and quantitative monitoring of the drying progression, but no single technique is fully satisfactory. Electrical and dielectric methods are difficult to automate and require temperature corrections, microwave sensors lack precision in the lower moisture range, while nuclear radiation devices arise safety concerns and require a knowledge of the bulk density of the material. Infrared backscattering techniques are convenient in the sense that they are rapid, noninstructive and thus easy to automate, accurate and independent on the material temperature or bulk density, but they are only sensitive to the surface moisture content within the penetration depth of the infrared beam, typically a few hundreds of micrometers, while being sensitive to species dependent surface characteristics.

An approach which is receiving an increasing amount of attention for moisture sensing is based on the evaluation of thermal properties. Moisture has long been known to affect the thermal properties of porous media such as the soil [14]. Single or double wire probes which are inserted into the inspected medium are used for the evaluation of the thermal conductivity and diffusivity of a range of porous materials such as the soil or building materials [15-18]. Thermal diffusivity is often found to be weakly and nonmonotonically correlated to the degree of moisture as compared to thermal conductivity [19]. Similar conclusions were recently reached on an investigation of moisture infiltration in polymeric materials by photothermal radiometry [20]. A similar approach, which has the advantage of being noncontact and thus easy to automate, has recently been applied by Forintek, Vancouver to the on-line evaluation of lumber moisture in drying mills [21, 22].

This paper presents an analysis of the different thermal parameters playing a significant role in the photothermal characterization of moist lumber, in-

cluding thermal conductivity, diffusivity and effusivity, specific heat, mass density and surface losses. A reflective cavity technique is described to reduce the dependence of photothermal measurements on variable wood surface characteristics. Experimental results obtained with a few Western Canadian wood samples at different moisture content levels are presented and discussed.

2. Theoretical background.

The basic elements of a photothermal characterization setup are shown in figure 1. Incident radiation, typically a pulsed laser beam, is absorbed by the front surface of the inspected material, raising its temperature to a certain level above ambient. Infrared detectors are used to monitor the temperature history on the front and/or the back surface of the inspected sheet. Material properties such as the presence of subsurface defects [23, 24], spectroscopic absorption [25], and thermal diffusivity of ceramic [26, 27] or polymeric [28] materials may be inferred from the temperature recordings.

Fig. 1. — Schematic diagram of a sheet submitted to photothermal analysis. D1, D2 : infrared detectors.

If a constant power flux Q per unit surface is absorbed at the front surface of a semi-infinite irradiated material during a time period τ , the surface temperature rise in the one-dimensional approximation [29] can be expressed using the superposition principle as

$$\Delta T = 2 Q (t)^{\frac{1}{2}} (\pi K \rho C)^{-\frac{1}{2}} - P(T), \quad t < \tau \quad (1)$$

$$\Delta T = 2 Q (\pi K \rho C)^{-\frac{1}{2}} \left[(t)^{\frac{1}{2}} - (t - \tau)^{\frac{1}{2}} \right] - P(T), \quad t > \tau$$

where K is the thermal conductivity, ρ the density, and C the specific heat of the inspected material, while $P(T)$ represents the temperature dependent heat losses due to air convection, radiation and phase changes. Figure 2 shows two typical front surface thermograms which will be discussed later.

The temperature evolution at the back surface of the finite thickness sample excited at its front surface by a short heating pulse is given in the one-dimen-

Fig. 2. — Surface temperature evolution of spruce sapwood samples submitted to laser irradiation for a period of 5 s. Top trace : moisture content 6.7 percent, incident laser power 1.2 W/cm². Bottom trace : moisture content 127 percent, incident laser power 5 W/cm². For both signals, the horizontal scale is 5 s/div. and the vertical scale is 0.1 V/div. corresponding to 6 degrees K/div.

sional approximation and neglecting surface losses by the familiar thermal response curve (a) of figure 3. From this curve, the thermal diffusivity $\alpha = K/\rho C$ of the inspected material can be evaluated using the expression [30]

$$\alpha = 0.139 d^2/t_{\frac{1}{2}} \tag{2}$$

where d is the sample thickness and $t_{\frac{1}{2}}$ is the half-risetime as shown in figure 3. Also shown in the same figure is the thermogram (b) computed by taking into account three-dimensional propagation effects in the anisotropic lumber material as well as surface losses. Computations were performed using a three-dimensional numerical model whose main characteristics are described elsewhere [31] with the parameters listed in table I.

Fig. 3. — Computed temperature evolution at the back surface of a wooden sheet, 3 mm-thick, thermally excited at its front surface by a 4 s-long rectangular laser pulse ; (a) extended surface heating, no surface losses ; (b) 4 mm $\times$ 4 mm heated area, including surface losses.

Table I. — Parameters used in the numerical thermal model for figure 3.

Parameter	Value
Thermal conductivity, x-direction	0.004 W/cm K
Thermal conductivity, y-direction	0.002 W/cm K
Thermal conductivity, z-direction	0.002 W/cm K
Specific heat	2 J/g K
Mass density	0.9 g/cm ³
Sheet thickness	3 mm
Heated surface	4 mm $\times$ 4 mm
Surface absorbed power	5 W/cm ² during 4 s
Surface losses	
(T = temperature in degrees K ; the ambient temperature is 293 K)	$5.7 \times 10^{-12} (T^4 - 293^4) + 10^{-3} (T - 293)$ W/cm ²

It follows from the above that thermal diffusivity can be evaluated from the thermogram recorded on the back of the pulse-heated sample by using equation (2) or, more reliably, by matching the experimental curve with a computed thermogram of the kind of curve (b) in figure 3. Alternatively, the thermal effusivity $e = (K\rho C)^{\frac{1}{2}}$ can be evaluated from equation (1) if the absorbed power Q and the heat losses are known and if the temperature elevation after a given heating period can be reliably measured. For instance, the peak temperature at the end of the 5 second heating period can be evaluated from thermograms of the kind shown in figure 2, higher peak temperature corresponding to lower thermal effusivities of the sample material.

The choice between a front or back surface thermal characterization approach should be made in terms of the specific application. Back surface measurements are convenient because they are not affected by reflected light noise, while the value of thermal diffusivity can be evaluated from the shape of the thermogram without requiring an absolute calibration of the detector. On the other hand, front surface techniques can be implemented on massive materials without the need to prepare a sample of given thickness, or to measure independently the sheet thickness in an on-line thermal characterization of sheet-like materials. Moreover, front surface temperature measurements provide higher signal levels and require shorter observation times.

Front-surface thermal effusivity measurements are in general more convenient than a thermal diffusivity analysis when evaluating material properties such as porosity. Indeed, both K and ρ increase with the sample density, so that their variations tend

to compensate each other and result in a relatively constant thermal diffusivity $K/\rho C$ as the material porosity varies. The product $K\rho C$ has been shown to be much more sensitive than thermal diffusivity to the density of sintered ceramics [32]. Similar, and even stronger, arguments in favor of a front surface approach are valid in the case of lumber moisture evaluation. In this case, the values of each of the parameters K , ρ , C as well as the surface evaporation losses $P(T)$ increase with moisture thus concurring to a large decrease of the irradiated sample peak temperature as its moisture content increases. Front surface temperature measurements are thus expected to be much more sensitive to lumber moisture than thermal diffusivity measurements, in agreement with previous experimental results obtained with polymer films [20]. The results presented below confirm such expectations and quantitatively evaluate the contribution of each thermal parameter to the variation of the peak surface temperature with the moisture content.

3. The reflective cavity technique.

In order to establish a reliable correlation between the surface peak temperature and the lumber moisture content, both the infrared evaluated temperature and the absorbed laser power per unit surface must be measured with repetitive accuracy. Such an accuracy cannot be assured if the surface absorptivity and infrared emissivity of the inspected sample may change unpredictably from point to point. To avoid these problems, a reflective cavity technique was developed for the photothermal evaluation of ceramics [32]. A highly reflecting hemispheric cavity with a small entrance hole is placed close to the surface of the inspected material, as shown in figure 4. Both the heating laser beam and the infrared temperature sensor are optically focused on the entrance hole. If the hole is sufficiently small and the cavity reflectivity high, multiple reflections of the laser radiation within the cavity lead to an almost total absorption of the laser beam by the sample surface, resulting in an effective sample absorptivity close to 100 percent. Similar considerations lead to a nearly 100 percent infrared emissivity from an opaque sample surface. Thanks to the cavity, the

Fig. 4. — Schematic diagram of the hemispheric cavity geometry. S : light source and/or infrared detector.

sample can be considered as a near-blackbody so that errors induced by variations of the actual absorptivity and emissivity of the materials are minimized.

Computations of the effective absorptivity of the hemispheric cavity as a function of the real lumber surface absorptivity are shown in figure 5. Curves (a) and (b) in this graph are obtained with $\theta = 15$ degrees for an inner cavity reflectivity of 97 and 85 percent, respectively, while curves (c) and (d) are the corresponding results at $\theta = 0$ degree. These curves were obtained by a Monte-Carlo computation with a hemispheric cavity of 12 mm radius, 3 mm hole diameter, situated at a 1 mm distance from a nearly Lambertian wooden surface and assuming a 0.16 numerical aperture for the incident beam. Even at a relatively low cavity reflectivity of 85 percent, we can see that the cavity substantially improves the effective absorptivity of the irradiated surface. For instance, the effective absorptivity is raised to nearly 90 percent for a real surface absorptivity of 60 percent. Similar results are obtained for the emissivity.

Fig. 5. — Effective absorptivity of a wooden surface irradiated through a hemispheric cavity as a function of the real wood absorptivity, for an inner cavity reflectivity of (a) 97 percent and (b) 85 percent at a viewing angle $\theta = 15$ degrees. Curves (c) and (d) are the corresponding computations at $\theta = 0$ degree.

4. Experimental results ; wood sample characterization.

Three kinds of wood, i.e. softwood (spruce, pine and fir) veneer, red cedar and spruce sapwood, were analysed during our investigation. Table II gives the dimensional characteristics of the samples used in our moisture analysis tests. Preliminary measurements were performed to evaluate a few relevant properties of the wood in question, namely the thermal conductivity, whose effects were neglected in previous investigations, and the spectral reflectivity, which is important in the choice of the infrared detector.

Table II. — *Characteristics of the wood samples.*

Wood species	Dry sample dimensions (cm, respectively in the longitudinal, tangential and radial directions)	Dry sample weight (g)
Softwood veneer	7 × 7.8 × 0.34	7.02
Spruce	7.1 × 5 × 0.38	4.45
sapwood	6.2 × 6.4 × 0.38	6.07
Red cedar		

The directional thermal properties of wood were evaluated both qualitatively, by spot heating and thermographic inspection, and quantitatively, by measuring the thermal propagation time through samples sectioned with different fiber orientation. The three basic directions in a tree are the longitudinal direction, parallel to the axis of the tree, the radial direction, perpendicular to the annual rings, and the tangential direction, parallel to the annual rings in a tree cross-section.

Figure 6 shows qualitative pictorial evidence of the thermal anisotropy of a 3.4 mm-thick veneer

Fig. 6. — Thermographic anisotropy analysis of a wooden sample spot heated by a focused laser beam on a surface containing the longitudinal and the tangential fiber orientation (top) and on a tangential-radial surface (bottom). Each picture displays the temperature distribution over a 2 cm × 3 cm area.

sheet, at 40 percent moisture content, with its main surface perpendicular to the radial direction. A 50 mW argon laser was focused to a 1 mm² spot on the wooden sheet whose surface was thermographically monitored with an AGEMA 782 infrared camera to follow the rate of heat diffusion from the laser heated spot in the different directions. As shown in the top thermograph of figure 6, the diffusion rate is higher in the vertical (longitudinal) direction as compared to the horizontal (tangential) direction. The isotherms displayed in the camera thermograph correspond to the temperature levels, in degrees C, shown on the right of each picture. The bottom thermograph of figure 6 was obtained by focusing the laser beam on one of the annual rings of a large knot on the same sheet. The isotherms are now roughly circular, showing that no appreciable thermal anisotropy exists between the radial and the tangential direction in a plane perpendicular to the tree or branch axis.

A more quantitative evaluation of the directional thermal diffusivity was carried out by sectioning 30 percent moisture red cedar samples with through-thickness axis in either the longitudinal, radial or tangential direction, and performing a flash thermometry analysis. The front surface of each sample was heated during a 1 s-period with a heating lamp, and the back surface temperature evolution was recorded with an infrared detector. By matching the thermograms obtained for each sample with numerically computed curves of the kind shown in figure 3, the thermal diffusivity values shown in table III were obtained. The above mentioned qualitative results about the presence of a fast axis in the longitudinal direction are confirmed. If we take into account the wood density data shown in table II, as well as the known specific heat values of 1 cal/g K for water and 0.25 to 0.35 cal/g K for wood [22, 34], we can conclude that the magnitude of the measured thermal diffusivity is in substantial agreement with the available thermal conductivity data [33].

Table III. — *Directional thermal diffusivities for a representative red cedar sample.*

Direction of thermal propagation	Thermal diffusivity (mm ² /s)
Longitudinal	0.41
Radial	0.15
Tangential	0.16

Other important parameters in a photothermal analysis are the absorptivity and the spectral emissivity of the wood surface. The absorptivity was evaluated at different wavelengths for different

wood samples in either a dry or a highly wet state. The absorptivity was measured by detecting the diffuse reflectance in a diffuse-white integrating cavity by a pivotable reference method of the kind described in ASTM Standard STM D-1033-61. The results are given in table IV.

Table IV. — *Measured absorptivity for different wood samples.*

Sample identification	Incident light wavelength	Surface absorptivity
Softwood veneer, dry	514 nm	0.80
Softwood veneer, wet	514 nm	0.84
Softwood veneer, dry	633 nm	0.53
Softwood veneer, wet	633 nm	0.52
Spruce sapwood, dry	514 nm	0.72
Spruce sapwood, wet	514 nm	0.83
Spruce sapwood, dry	633 nm	0.55
Spruce sapwood, wet	633 nm	0.57
Red cedar, dry	514 nm	0.88
Red cedar, wet	514 nm	0.95
Red cedar, dry	633 nm	0.76
Red cedar, wet	633 nm	0.86

As to the spectral emissivity, figure 7 shows the diffuse reflectance spectrum of light reflected from softwood veneer at 15 percent moisture. The spectral distribution was recorded with an FTIR spectrometer and was normalized by reference with the spectrum obtained from a KBr powder sample whose reflectivity is uniformly close to 100 percent. Similar spectra, except for an accentuation of the 1.4 and 1.9 μ m absorption bands, were obtained with samples of different species having a larger moisture content. For an opaque, diffuse material as our lumber sample, the spectral emissivity and the spectral reflectivity must sum up to unity. We can thus conclude that the infrared emissivity in the

Fig. 7. — Diffuse spectral reflectance of light from a softwood veneer sample, 15 percent moisture content, with reference to KBr powder.

spectral region between 3 and 5.5 μm corresponding to the sensitive range of our InSb detector is higher than 90 percent. An even higher emissivity, of the order of 98 percent, would be obtained by using an infrared detector with sensitive range in the 8 to 14 μm region.

5. Experimental results ; photothermal moisture evaluation.

For moisture evaluation, the wood samples described above were preliminarily soaked in water for several days to reach their maximum moisture content. Photothermal tests were then performed on the samples after subsequent drying periods in an oven followed by weighing. Complete dryness was assumed after the last drying cycle of two days at 110 °C.

Fig. 8. — Schematic diagram of the experimental setup for the photothermal moisture analysis. D1, D2 : infrared detectors ; BS : dichroic beam splitter.

A diagram of the experimental apparatus for the photothermal measurements is shown in figure 8. An argon-ion laser beam of 1 W continuous power was used to irradiate a 5 mm-diameter area on the wooden sample through an out-of-center hole on the reflective cavity. The front-surface temperature history was recorded through a laser reflecting, infrared transmitting dichroic beam splitter by a chopped, cryogenically cooled InSb infrared detector. Thermograms of the kind shown in figure 2 were recorded by this detector. The back-surface temperature evolution was recorded with a low speed, ambient temperature thermopile detector. A typical thermogram obtained by this detector is shown in figure 9a. Also shown in figure 9b is an example of the detection problems created by moist air convection flow in front of the infrared detector when high moisture samples were inspected. To avoid these problems and obtain curves such as figure 9a, high moisture samples were wrapped in a thin plastics film transparent to both the laser and the infrared radiation. No similar problems were observed for the front-surface infrared measurements, partly because of the higher temperature signals reached on the front surface and of the lower spectral sensitivity to water vapor of the InSb detector, and partly

Fig. 9. — Back-surface thermograms obtained with a spruce sapwood sample, 100 percent moisture content, front-surface excited by an 8 s-long, 5 W/cm² laser irradiation, (a) with moist-air convective flow protection, and (b) without convection protection. Horizontal scale : 5 s/div. ; vertical scale : 20 mV/div., corresponding to nearly 2 K/div.

because of the protection from convective flow provided by the hemispheric cavity. With a laser irradiation period of 4 s and a sample thickness of nearly 4 mm, it can be considered that the thermal front has not yet reached the back surface at the end of the heating period, so that the value of the peak front surface temperature is not affected by the finite thickness of the slab.

For each value of the moisture content, as determined by precise weighing, both the peak temperature at the end of a 4 s heating period and the thermal diffusivity, determined by matching the experimental thermogram with numerically computed curves of the kind shown in figure 3b, were recorded. Plots of these two parameters as a function of moisture content for three lumber species are given in figure 10. A number of conclusions can be drawn from an analysis of these results :

- the much higher sensitivity to moisture content of the front temperature rise ΔT as compared to the thermal diffusivity α is apparent. This is a consequence of the fact, as mentioned above, that the variations of the lumber density, specific heat, thermal conductivity, and vaporization losses all tend to decrease the front temperature rise when the moisture content increases, while they tend to compensate each other as far as the thermal diffusivity is concerned ;

- the differences among the temperature vs. moisture curves obtained with the three softwood species used in our investigation appear to be not far from the experimental error which is of the order of 5 percent moisture, and which is partially due to variations of the moisture content during measurement and across the sample ;

Fig. 10. — Experimental plots of (a) the front-surface temperature rise after 5 W/cm^2 laser irradiation during 4 s, and (b) the measured thermal diffusivity as a function of percent moisture content for the three lumber samples described in table II.

— the front surface temperature reaches relatively high levels with low-moisture materials, arising material damage concerns in industrial applications; one way to reduce the temperature excursion signal would be to insert a feedback loop switching off the heating power when a predetermined temperature level has been reached, and measuring the length of the heating period or the total source energy, as described in reference [35].

A quantitative analysis of the experimental results was performed in order to estimate the relative contribution of each thermal parameter appearing in equation (1) to the peak temperature signal evolution as a function of the moisture content. Table V shows the evolution of a number of parameters for the softwood veneer sample at different moisture content. Included are the experimentally measured values of the sample mass, thermal diffusivity α and peak front temperature ΔT , as well as the corresponding values of the mass density ρ , specific heat C , conductivity K and thermal effusivity e calculated as specified in footnote on the table. The tabulated values are given as the ratio of the parameter level at a given moisture and the level of the same parameter, with subscript d, for the oven-dry sample.

Figure 11 shows, based on the data of table V, the evolution of the thermal conductivity and effusivity at different moisture levels of one of the wood samples as compared to the experimental values of the front surface temperature rise. The following observations can be made from this figure:

— the thermal conductivity K increases substantially with the moisture content, so that its variation

Table V. — Experimental and computed thermal parameter variations at increasing moisture levels for the softwood veneer sample.

(a) Sample mass, g	(b) ρ/ρ_d ⁽¹⁾	(c) C/C_d ⁽²⁾	(d) α/α_d	(e) K/K_d ⁽³⁾	(f) e/e_d ⁽⁴⁾	(g) $\Delta T_d/\Delta T$
7.0	1.0	1.0	1.0	1.0	1.0	1.0
7.2	1.02	1.05	0.95	1.02	1.05	1.08
8.1	1.13	1.27	0.91	1.29	1.36	1.35
8.4	1.18	1.35	0.9	1.43	1.51	1.57
9.7	1.35	1.60	0.85	1.84	1.99	2.0
10.7	1.48	1.75	0.84	2.2	2.39	2.64
10.9	1.5	1.78	0.85	2.27	2.46	3.08
13.1	1.78	2.0	0.75	2.67	3.08	4.23
14.1	1.9	2.1	0.71	2.83	3.36	5.92
15.0	2.0	2.17	0.67	2.91	3.55	6.43

⁽¹⁾ Evaluated from (a) by taking into account the experimentally monitored sample swelling.

⁽²⁾ Computed from (a) assuming a linear superposition of the free water specific heat of 1 cal/g K and of the lumber specific heat estimated at 0.3 cal/g K .

⁽³⁾ Inferred from (b), (c) and (d) as $K = \alpha \rho C$.

⁽⁴⁾ Inferred from (b), (c) and (e) as $e = (K \rho C)^{1/2}$.

Columns (a), (d) and (g) are experimental data.

The subscript d refers to the oven-dry values.

Fig. 11. — Moisture-related variation of (a) the thermal conductivity, (b) the thermal effusivity, and (c) the front-surface peak temperature rise under laser irradiation as evaluated in table V for the softwood veneer sample.

in the case of a thermally thick slab contributes significantly to the temperature vs. moisture signal. It should be noted that the thermal conductivity displayed in figure 11 refers to the radial or tangential direction, while different results may be obtained for the longitudinal direction as mentioned in section 4 above. This is of little concern in practice, as the through-thickness direction of boards is almost always radial or tangential;

— the variation of the thermal effusivity $e = (K \rho C)^{1/2}$ can be seen from figure 11 to be mostly

responsible for the increase of the signal with the moisture content up to a moisture level of nearly 40 percent. With reference to equation (1), it can be concluded that the surface losses $P(T)$ have only minor effects on the amplitude of the temperature rise signal at low moisture levels, while having a predominant effect on the amplitude of such signal at moisture contents of the order of 100 percent. This appears to be related to the fact that up to nearly 30 percent, the moisture is in the form of bound water, while the rest is in the form of free water which is very mobile through capillarity (Ref. [1], p. 19).

This conclusion is in agreement with a qualitative analysis of figure 2 above. The different shape of the two thermograms shown in this figure is readily apparent. While the top curve shows a temperature rise during laser irradiation closely following the $t^{\frac{1}{2}}$ progression expected from equation (1), the bottom curve has a visibly different shape. In the latter case, which corresponds to a much higher moisture level, the temperature rise is steep at the beginning, in agreement with a power density 4 times larger than for the top curve, but soon saturates to reach substantially the same temperature level at the end of the 5 s heating period. The reason for such a behaviour is now apparent : at high moisture levels, surface evaporation losses become preponderant as soon as the temperature of the water film at the wood surface is raised above ambient, and such losses hold down the temperature rise during the laser irradiation period.

6. Discussion.

A first point on which we would like to make a few comments is that of the depth of probing. Such a discussion is particularly relevant when comparing the photothermal technique analysed in this paper with the infrared spectroscopy approach, whose main drawback as discussed in section 1 above is that it is only probing the moisture content within a skin depth of a few hundreds of micrometers, or even smaller at low moisture levels.

At high moisture content levels, it was observed above in the analysis of figure 11 that the surface evaporation losses play a predominant role in the variation of the temperature rise signal with the moisture constant. If we take into consideration the small value of the moisture diffusivity coefficient in the radial or tangential direction, we can conclude that the probing depth reached with a photothermal technique is hardly higher than the infrared penetration depth obtained by the spectroscopic technique at high moisture levels. Conversely, in the industrially more important range of 0 to 40 percent it was observed above that the main mechanism for the temperature rise vs. moisture variation is of

thermal nature. Consequently, the probing depth is here associated with the thermal propagation depth which is of the order [29] of $d \approx (4 \alpha t)^{\frac{1}{2}}$, or a probed depth of a few millimeters for a heating period of a few seconds.

Also related to the vaporization vs. thermal regime is the analysis of the photothermal measurement reliability. The repetitivity of the temperature vs. moisture calibration curve is expected to be lower in the vaporization-controlled high moisture range, where the signal amplitude may be affected by changes in the relative air humidity, ambient air circulation and lumber microstructural properties affecting the directional moisture diffusivity coefficient. The calibration curve in the high-moisture regime may also be affected by the level of the injected energy, as illustrated in figure 12. Surface drying by the first laser irradiation is here seen to result in a higher second-pulse peak temperature. Such effects were less visible in the low-moisture range, where surface vaporization occurs to a minor extent. A differential approach of the kind described in reference [35] might be taken into consideration to evaluate the amount of free moisture in the irradiated volume.

Fig. 12. — Front-surface temperature signal obtained under two subsequent laser irradiations of the same spot on a spruce sapwood sample at 80 percent moisture content. Horizontal scale : 5 s/div ; vertical scale : 20 mV/div corresponding to a peak temperature for the first irradiation of 20 K above ambient.

In the low-moisture regime, the temperature vs. moisture calibration is dependent upon the value of the wood thermal effusivity $(K\rho C)^{\frac{1}{2}}$, and thus upon the variations of the thermal conductivity, mass density and specific heat from species to species [1, 33, 34]. Within a given species, variations of the

order of 50 percent are found for the thermal conductivity depending on whether the longitudinal direction is parallel or perpendicular to the inspected surface, as can be seen from table III. This is of little practical concern, however, since the boards are almost always sectioned parallel to the longitudinal direction. It should be noted at this point that the moisture content may vary by large amounts within the same board for reasons related to gravity,

convective flow patterns or fiber orientation. A visualization of such variations is given by figure 13, showing the thermal image of a veneer slab uniformly heated to nearly 10 K above ambient by a wide-area ceramic heater and let free to cool down through vaporization. The inspected surface of the slab was black painted to avoid any emissivity variations across the surface. The thermal image clearly shows a cooler temperature on the left

Fig. 13. — Top : photo of a typical 30 cm $\times$ 30 cm $\times$ 0.4 cm veneer slab ; bottom : thermal image of the same board after uniform heating followed by open-air cooling for 3 minutes.

portion of the slab, which was artificially moistened to a level higher than the right half, as well as a higher temperature for the knots, which are known to dry at a faster pace than the surrounding material because of their surface-open longitudinal fibers. Under such circumstances, it can be understood that a moisture content for a given board may only be specified as the average of a relatively wide distribution.

Another question of practical concern is whether a reflective cavity in close proximity to the inspected surface is always necessary. Although such a configuration is conceivable for a stationary, manually held spot probe, the requirement for a quasi-contact with the lumber surface makes the automation of the sensing process difficult, particularly in a continuously moving drying line. Figure 7 shows that the increased emissivity made possible by the use of the cavity is of little consequence if we choose a detector with sensitive spectral region in the 8 to 14 μm range, where the wood emissivity is already close to 100 percent. As to the increased absorptivity offered by the cavity, it is indeed useful if we use a visible or near-infrared heating source such as an inexpensive tungsten lamp. The reflectivity of such a radiation from the lumber surface is of the order of 50 percent or higher. A back reflector, or a backscattered-light monitoring detector, should thus be used in conjunction with the heating lamp to avoid, or compensate for, random variations of the lumber surface absorptivity.

Finally, a point of practical importance for the on-line applicability of this technique is the advisability to limit the heating period to a sufficiently short observation time in order to make sure that we are always in a thermally thick regime, i.e. that the thermal propagation front does not reach the back front of the board during the observation time. If this was the case, i.e. if thermally thin slabs were to be inspected, the front surface temperature would rise proportionally to t , rather than $t^{\frac{1}{2}}$ as stated by

equation (1), and the calibration curve would become thickness-dependent. In order not to exceed the thermally thick regime, the observation time should not exceed a period of $0.1 d^2/\alpha$, with typical values for α given by table III.

7. Conclusion.

A photothermal approach for the indirect evaluation of moisture content in lumber has been analysed both theoretically and experimentally. The contributions of each thermal parameter to the amplitude of the detected signal have been clarified. In the low-moisture range, where most of the water is bound, the signal variation with moisture is mainly determined by the joint variations of the wood thermal conductivity, specific heat and mass density, the relative contributions of each of these three variables being of the same order of magnitude. At higher moisture levels, surface water vaporization losses become predominant. The fact that all of these parameters contribute to the decrease of the temperature rise signal amplitude with increasing moisture makes the photothermal approach much more sensitive to moisture variations as compared to a measurement of the thermal diffusivity. The signal variability associated with variations of the surface absorptivity across the board can be minimized by the use of a reflective cavity, while an independent evaluation of the board thickness is not necessary as long as the observation time is kept smaller than the thermal propagation time through the board.

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