Proceedings
22nd International Nondestructive Testing and Evaluation of Wood Symposium
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Abstract

The 22nd International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the Université Laval in Quebec City, Canada, May 24–27, 2022. This symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many international researchers, NDT/NDE users, suppliers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, structural lumber, engineered wood products, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world. A special on-line session was conducted to accommodate individuals who could not attend in-person due to the ongoing COVID-19 pandemic. The technical content of the 22nd symposium is captured in these proceedings. Full-length, in-depth technical papers for most of the oral presentations, along with abstracts for all the oral and poster presentations, are published herein. The papers were not peer reviewed and are reproduced here as they were submitted by the authors.

Keywords: Nondestructive evaluation, nondestructive testing, wood properties, wood products, logs, trees, wood structures

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Estimation of the Moisture Content in Wood by Combination of Neutron and X-Ray Imaging

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Abstract

Recent advances in image processing and X-ray computed tomography (CT) led to substantial development in the non-destructive estimation of the moisture content (MC) in wood, but a real-time technique is not yet available. The use of dual-energy CT has been proposed, but not yet proven due to the similarities of X-ray attenuation in wood and water. Neutron imaging (NI) provides an opportunity due to the large difference in the interactions of neutrons with hydrogen and carbon. The equipment available at the Paul Scherrer Institute (Switzerland) makes it possible to scan wood simultaneously with both neutron and X-rays in a climate chamber, so that changes in the moisture distribution with time can be studied through both methods. The aim of these studies was to increase basic knowledge of how the use of neutrons and X-rays in combination can be applied to study wood-moisture interactions and moisture flow in wood and wood-based products. Wood specimens conditioned to different MCs have been exposed to varying climate conditions and scanned with both techniques in the three main anatomical directions. The results have been processed by an advanced image-processing algorithm for MC calculation from both NI and X-ray imaging data. A preliminary analysis of the results suggests that the NI technique may be used to estimate MC with an accuracy equivalent to that of CT-based techniques, but further analyses and statistical studies are needed.

Keywords: neutrons, industrial X-ray computed tomography, dual energy, timber drying

Introduction

Recent advances in image processing in combination with discrete or computed tomography (CT) X-ray techniques have led to a substantial development of non-destructive detection of internal features of logs and sawn timber in industrial applications. The accuracy of X-ray measurements needs, however, to be
improved to be able to take full advantage of these techniques to give, for example, the accurate detection of properties and structures in the wood material as a basis for the further optimisation of sawing, drying, product sorting and grading, etc. It is a great challenge in image processing to assess the water present in green wood since water and wood have very similar X-ray attenuation coefficients (Couceiro et al. 2019), making it difficult to distinguish wood features when liquid water is present. From basic studies of moisture behaviour in wood in different climate environments using a combination of neutron and X-ray sources, we believe that the industrial X-ray detection in wood applications can be improved.

Due to the high hydrogen content of water, neutrons are more suitable for detecting water in, for example, wood, but neutrons and neutron sources are, at least for the foreseeable future, not suitable for industrial use for health and safety reasons. The investment and operating costs of the neutron facilities are also very high and the number of facilities in the world is limited. One such facility is available at the Paul Scherrer Institute (PSI) in Villigen, Switzerland. The equipment available at the Laboratory for Neutron Scattering and Imaging at PSI makes it possible to scan wood simultaneously with both neutron and X-rays in a climate chamber and to study the evolution of moisture distribution over time with both sources.

The overall purpose of this project is threefold: (1) to compare the information obtained from X-ray and neutron imaging, and to studying how this information can be combined and used to improve the X-ray CT-scanner detection at the CT WOOD laboratory at Wood Science and Engineering, Luleå University of Technology in Skellefteå, Sweden, (2) to study surface phenomena when drying with the help of neutron radiation, since technologies based solely on X-ray cannot properly represent the surface due to the so-called Gibbs phenomenon, and (3) to study moisture transport through adhesive bond-lines and wood-welding joints under varying humidity and temperature conditions above and below 0°C.

This paper focuses on the central question that must be solved before more detailed studies are carried out on wood: whether the moisture level of the wood can be continuously determined in the experiments described here, when it is expressed as the dry weight moisture content (MC) according to:

\[ \omega = \frac{m_\omega - m_0}{m_0} \]  

where \( \omega \) is the MC, \( m_\omega \) is the mass of the wood at the MC \( \omega \), and \( m_0 \) is the dry mass of wood.

**Theory**

The attenuation of a neutron or X-ray beam is dependent on the properties of the material through which the beam is travelling, as described by the Beer-Lambert law:

\[ T = \frac{I}{I_0} = e^{-\int_0^l \Sigma(z)dz} \]  

where \( T \) is the extent to which the material transmits the beam, \( I \) is the intensity of the attenuated beam, \( I_0 \) is the initial intensity of the beam, \( \Sigma(z) \) is the linear attenuation coefficient and \( l \) is the path length of the beam through the material. According to Jackson and Hawkes (1981), the attenuation coefficient of a material can be expressed as the sum of the gravimetric proportions of the attenuation of each of its components, so that the attenuation coefficient for wood can be expressed as:

\[ \Sigma_{i=1}^n \Sigma_i z_i = \Sigma_w z_w + \Sigma_h z_h + \Sigma_{v.s} z_{v.s} \]  

where \( \Sigma_w \) is the linear attenuation coefficient of wood \((w)\), \( \Sigma_h \) is the linear attenuation coefficient of water \((h)\), \( \Sigma_{v.s} \) is the linear attenuation coefficient of the void space \((v.s)\), \( z_i \) is the thickness of the discrete layer.
of dry wood, \( z_h \) is the thickness of the discrete layer of water and \( z_{v,s} \) is the thickness of the discrete layer of the void space. Neglecting the transmission of the void space and rewriting Eq. 2, the transmission over a certain time \( (i) \) can be described by:

\[
T_i = e^{-(\Sigma w z_w + \Sigma z_h (z_h)_i)}
\]  

(4)

Considering the definitions of density for dry wood, compact wood and water, Eq 1 can be expressed as a function of time \( (i) \):

\[
\omega = \frac{\rho_h (z_h)_i}{\rho_{cw} z_w}
\]

(5)

where \( \rho_h \) is the density of water, \( z_h \) is the thickness of the discrete layer of water present in the specimen, \( \rho_{cw} \) is the density of compact wood, and \( z_w \) is the thickness of the discrete layer of wood. If the MC is known on two occasions:

\[
\omega_i = \frac{\rho_h (z_h)_i}{\rho_{cw} z_w}
\]

(6)

\[
\omega_{n+1} = \frac{\rho_h (z_h)_{n+1}}{\rho_{cw} z_w}
\]

(7)

where \( n \) is the number of measurements, the thickness of the discrete layer of wood \( z_w \) can be expressed as:

\[
z_w = \frac{\rho_h ((z_h)_{n+1} - (z_h)_i)}{\rho_{cw} (\omega_{n+1} - \omega_i)}
\]

(8)

By using the Hounsfield scale, the density of wood can be calculated from the X-ray data as:

\[
\rho \approx 1000 \frac{\mu - \mu_h}{\mu_h - \mu_{v,s}} + 1000
\]

(9)

where \( \mu \) is total linear attenuation coefficient, \( \mu_{v,s} \) is the linear attenuation coefficient of air, and \( \mu_h \) is the linear attenuation coefficient of water. Since the attenuation coefficient of a material can be expressed as the sum of the gravimetric proportions of each of its components, the density can be expressed by:

\[
\rho \approx 1000 \frac{(\mu_w z_w + \mu_h z_h + \mu_{v,s} z_{v,s}) - \mu_h}{\mu_h - \mu_{v,s}} + 1000
\]

(10)

where the \( \mu_w \) is the linear attenuation coefficient of wood. When a given wood specimen undergoes a change in moisture, approximately only the change in the spatial distribution of water \( z_h \) takes place. Thus, the neutron transmission of a reference piece of wood can be expressed as:

\[
T_i = e^{-(\Sigma w z_w + \Sigma z_h (z_h)_i)}
\]

(11)

Dividing the transmission at a certain point in time \( (T_{n+1}) \) by the transmission for the reference piece of wood \( (T_i) \), the change in the spatial distribution of water can be expressed as:
\[ ((z)_{n+1} - (z)_i) = -\frac{\ln\left(\frac{T_{n+1}}{T_i}\right)}{\Sigma_h} \] 

(12)

The thickness of the discrete layer of wood \( z_w \) can thus be estimated if neutron scanning has been carried out on two occasions, where the test piece has undergone a moisture change. If the MC is known on these two occasions, the MC can be calculated at all times where a neutron image is determined. Rearranging Eq. 8 and combining it with Eq. 12, the MC variation over time can be estimated as:

\[ \omega_{i+1} - \omega_i = \frac{\rho_h}{\rho_{cwz_w\Sigma_h}} ((z_h)_{i+1} - (z_h)_i) \] 

(13)

If the initial value of the MC is uncertain, it is possible to estimate this uncertainty if the dry density of the wood, the MC at the end of the experiment, the thickness of the test piece in the neutron beam direction and the thickness of the discrete layer of water at the beginning and at the end are known. By rearranging equation (13) and using the definitions for the compact density of wood and the density of dry wood, the MC at the start of the experiment can be estimated as:

\[ \omega_1 = \omega_{n+1} - \frac{\rho_h}{\rho_{d,w\Sigma_h}} ((z_h)_{n+1} - (z_h)_1) \] 

(14)

### Materials and methods

Specimens of green Scots pine (\( Pinus sylvestris \) L.) sapwood with dimensions of 10 x 10 x 50 mm were used. The specimens were cut with specific orientations in relation to the three main anatomical directions of wood – longitudinal (L), radial (R) and tangential (T) –, so that four types of specimens were prepared, giving different possible relations between growth-ring orientation and the neutron and X-ray beam directions, as shown in Figure 1. All the specimens were taken from the same region in one tree and cut in a way so that they matched each other as well as possible with respect to the orientation of the growth rings. The specimens were sealed using aluminium tape along four of their sides so that the moisture uptake and drying could take place only in one direction, perpendicular to the beam (Figure 1). The specimens were conditioned to different MCs or kept in the green condition and sealed in plastic film to avoid uncontrolled MC changes prior to the experiments.

![Figure 1](image)

**Figure 1**—The configurations of specimens (types 1 to 4) used in the experiments, and their positions relative to the beam direction and the moisture flow, due to the restriction of moisture movement with aluminium foil sealing.
The experiments were performed at the NEUTRA beamline at Paul Scherrer Institute, Villigen, Switzerland. The experimental setup consisted of a specially designed climate chamber (Mannes et al. 2017), which was mounted in the Neutron/X-ray beamline, followed by a scintillator-camera based detector (cf. Lämmlein et al 2019). The specimens were placed in an aluminium rack which holds up to eight specimens and were placed inside the climate chamber (Figure 2).

The specimens were weighed in order to calculate gravimetrically their initial average MC and then placed on the aluminium rack inside the climate chamber. They were then scanned under an 18-hour cycle with varying relative humidity (RH) at a constant temperature of 60°C. The initial RH in the chamber was, after a 30 min stabilisation regime at 76% RH, 90% (5.5 h), and it was then lowered stepwise (2x4 h) to a final 30% (4 h).

Since images obtained contain anomalies, they had to be processed before using them for the calculations. This processing entails open beam correction to decrease the noise and black body correction (Boillat et al. 2018; Carminati et al. 2019a) to reduce the scattering effects. These image processing steps are implemented in the software Kiptool (Carminati et al. 2019b).

Results and discussion

The results of the MC calculations showed considerable discrepancies compared to what was expected based on the equilibrium MC (EMC) of the climate over time (Figure 3). The results for only 2 of the 8 specimens were chosen for an in-depth analysis, both corresponding to specimen type 2, designated as specimen A and B. These are pointed out in Figure 3 and shown in Figure 4 as neutron images. Specimen A had an initial MC slightly over 0%, whereas specimen B had an initial MC of almost 120% (green state).
Figure 3—Evolution of the MC of the 8 specimens (left: low initial MC, type 1-4 and, right: initial green MC, type 1-4) during the experiment, and the equilibrium EMC corresponding to the climate in the chamber over time. Specimens A and B are indicated.

Figure 4—Neutron imaging of specimens A (left) and B (right) at Time = 0 h, with water movement taking place in the radial direction. High brightness in the images indicates large attenuation of the beam interacting with the specimen, thus high MC. In specimen B it can clearly be seen that the surface region of the specimens has dried before the start of the neutron scanning.

The unexpected errors in the MC calculation mentioned in the theory section may be due to small MC differences within the specimen at the start of the experiment. These differences appear to play a much greater role than expected in the accuracy of the calculations. Even when the specimens were conditioned, handling them before the experiment seems to have caused a water uptake or drying sufficiently high for the surfaces to show a higher/lower MC than the core of the specimens. To correctly estimate the initial MC at the pixel level, these moisture differences must be taken into consideration. These moisture differences can be estimated by dividing the specimen into regions, in this case three layers, and calculating the MC and density independently for each of them with help of X-rays, and then using Eq. 14 to estimate the initial MC of each layer. This method was applied for specimens A and B, and the results show that the layer-wise MC estimation, as shown in Figure 5, leads to a more accurate result in relation to the EMC at a given time.
Specimen A was oven-dried, so its initial MC should be quite similar, but due to possible differences between the surface and core regions, the MC estimation based on different initial MCs seems more plausible during the entire climate cycle. In the case of specimen B, even if the bottom left-hand graph in Figure 5 seems to be more plausible than the bottom right-hand graph due to the apparently more similar MCs in the three different regions, that is not the case. The initial MC that was originally estimated as a single value for the entire piece is clearly shown in Figure 4 not to be a correct assumption (note the brighter colour in the centre of the specimen and the darker colour closer to the edges). When the initial MC was estimated separately for the three regions shown in Figure 5, the initial MC of specimen B seemed to match the image in Figure 4 more accurately, as does the evolution of the MC towards a more homogeneous MC as the climate change proceeds.

Conclusions

The combination of neutron and X-ray imaging is a powerful tool for estimating the MC in wood at a very detailed level. MC calculations were found to have considerable discrepancies compared to what was expected based on the EMC of the climate over time, and the known initial conditions of the wood specimens. This has been shown to be because the initial MC was not correctly estimated. By dividing the wood into three different regions during the image analysis, the initial MC could be estimated separately for each region and the MC could be estimated more accurately. The method and technique shown in this study will be used for a complete statistical analysis of the data collected in this project, and the method will be developed as a tool for future projects in the field of wood and water interactions.

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References


