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Neutron imaging of moisture displacement due to steep temperature gradients in hardwood

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ABSTRACT

One-side heating of moist wood results in the propagation of a drying front, which forces moisture ahead. This wet forefront occurs where the temperature downstream drops below 100 °C. The dynamics of moisture displacement in hardwood (beech) during one-side heating, leading to steep temperature gradients, is documented by means of thermal neutron radiography. Wood samples with initial hygroscopic moisture content in the 12–14% range are put in contact with a foil at 150 °C or at 250 °C for 40 min in a line of neutron radiography setup. Neutron imaging documents the moisture redistribution, while thermocouples document the temperature gradient. As the temperature increases in the material, moisture is desorbed and displaced downstream of the heat source, resulting in a zone with increased moisture content ahead of the drying front. The redistribution of moisture content has specific patterns in the three orthotropic directions, with a larger moistened zone in longitudinal direction, and growth ring related features in the radial and tangential directions. The desorption zone undergoes shrinkage which is documented by the radiographs.

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1. Introduction

The rapid displacement of moisture in a hygroscopic porous media driven by a high temperature gradient is a complex problem, where the heat and mass transport phenomena depend in a coupled manner on temperature and moisture content [1–3]. In addition, changes of moisture content result in swelling or shrinkage of wood, leading to a coupled hygro-thermo-mechanical behavior. Wood is a cellular material, where most of the cells, named fibers, are oriented longitudinally, i.e. along the tree trunk direction, while a small proportion of them, named rays are oriented radially. In hardwood, a larger longitudinal feature is present, vessels which are surrounded by fibers. Wood grows seasonally which results in growth rings alternating low density earlywood, composed of thin wall fibers with large lumen, and high density latewood, composed of thick wall fibers with small lumen. Fig. 1 shows the cellular structure of European beech (Fagus sylvatica). This image, acquired by synchrotron X-ray microtomography at TOMCAT SLS, Paul Scherrer Institute (PSI), shows the vessels of hardwood ranging from 350 μm in diameter in earlywood to 50 μm in latewood. Stacks of rays, called multiseriate rays, are also visible.

Understanding the coupled processes of heat and moisture transport in wood is relevant for treatment and modification processes such as thermal modification [4–6], densification [7] and welding [8,9]. These processes are becoming increasingly popular in the forest products industry, though little is known and understood about what is happening in the material during such treatments. The transport properties of wood depend on the material orientation, namely the longitudinal, radial and tangential directions [10–12]. Thermal conductivity and vapor permeability are higher along the longitudinal directions compared to the transversal ones and depend on temperature and moisture content [13–15]. In addition, mechanical properties, including those related to dimensional changes, are heat and moisture dependent [16–20]. In the hygroscopic range, which is approximately below 28% moisture content mass per mass, wood swells volumetrically by 10–12% [21].

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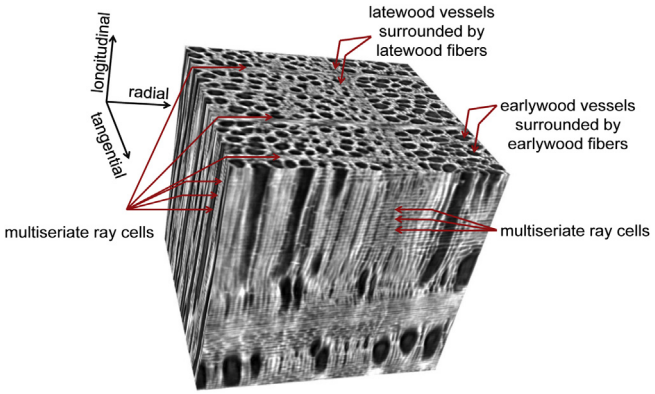

Fig. 1. Microtomography of beech showing the anatomical features such as fibers, vessels and rays, size: 1200 × 1200 × 1200 μm^3.

Moisture added above this level is found in the cell lumen in liquid phase [13]. Hygroscopicity decreases with increased temperature [22,23]. From 80 °C is the onset of heat softening of the material. Temperature rise above 150 °C leads to strong variations of wood mechanical properties, as the ultrastructure of cell walls degrades at these temperatures, due to decomposition of the biopolymers and changes in structure of the cellulose microfibrils [24,25]. Wood undergoes some thermal expansion, with a coefficient in the transverse directions of about 3×10^{-5} m/m K. Few hygro-thermo-mechanical tests for temperature above 100 °C under controlled moisture conditions have been performed [16–18]. Studying timber structural elements, White and Schaffer (1981) measured the moisture accumulation in a fire exposed wood slab using moisture sensors and reported that, under high temperature gradients, moisture migrates along the direction of heat flux and is displaced significantly ahead of the drying zone [26]. This temperature-driven moisture redistribution in wood has been shown to play an important role on the performance of timber structural element, such as connections [27]. Recently, we have used thermal neutron radiography to document the heat induced moisture transport in wood, at a resolution higher than that of magnetic resonance imaging and X-ray radiography [28]. High resolution of neutron radiography for investigation of moisture transport is due to the high attenuation of the neutron beam by hydrogen nuclei of water [10,29]. In this first experiment, the dependency of moisture migration on the geometry of growth rings layers, for one softwood and one hardwood species was studied. However, the samples were left exposed to air on all surfaces, resulting in complex observed moisture redistribution patterns.

In this article, the hygro-thermo-mechanical behavior of moist hardwood exposed to high temperature is investigated. The wood samples are shielded, to ensure adiabatic boundary conditions at all vertical faces and thus one dimensional heat and moisture transport, and heated at their base to 150 °C and 250 °C as neutrographies are acquired. The two-dimensional projections document the distribution of moisture content, in the plane of image acquisition. The redistribution of moisture during 40 min of heating is documented and analyzed together with the measured temperature gradients and also dimensional changes.

2. Materials and methods

In this section, first we introduce the experimental methodology including sample preparation, description of heating device, image acquisition facility and experimental procedure. Then in the second part, the method of image analysis is explained.

2.1. Methodology

2.1.1. Sample preparation

Six samples of beech (Fagus sylvatica) were cut side by side out of the same wood plank, all quarter-sawn in dimensions of 80 (width) × 40 (height) × 10 (thickness) mm^3. Then they were oven dried at 80 °C and weighted with a precision balance (±0.0001 g accuracy) to obtain their dry mass and density. 8 holes of 0.4 mm diameter and 20 mm length were precisely drilled along the sample height with fine drilling machinery, for positioning the thermocouples at different distances from the heating foil as described below. Then the samples were conditioned for one week in an 80% relative humidity (RH) chamber at 25 °C until equilibrium. Depending on the heat flow directions along the orthotropic directions of wood, samples are referred here as longitudinal, tangential or radial (Fig. 2).

2.1.2. Heating device

The heating device consists of a heating foil of 0.05 mm, placed on a thermally insulating ceramic sheet. Heat is provided by a power supply of maximum 50 A and 120 V. The temperature is measured by two thermocouples, positioned between the foil and the ceramic sheet and is used in the power supply control algorithm implemented in Labview. Type E (NiCr–CuNi, 100 μm) thermocouples are used for measuring the temperature inside the samples. All thermocouples are calibrated in an ice/water bath at 0 °C. In Fig. 3(a), a schematic view of the heating device is presented.

2.1.3. Image acquisition facility

We used the imaging facilities of the Neutron Transmission Radiography (NEUTRA) beamline at the SINQ, PSI, in Switzerland, for imaging and quantification of moisture content distribution in the wood samples during the heating experiments. Neutron radiography at the NEUTRA station relies on a neutron beam within the thermal spectrum, with a most probable energy level of about 25 meV [29]. In Fig. 3(b), the schematic overview of the neutron beamline is shown. The *x*- and *y*-axes correspond to the detector plane axes while the *z*-axis shows the neutron beam direction. The detector consists of a scintillator-CCD camera-system, with a total field of view of 150 × 150 mm^2. The scintillator is made of a 100 μm thick layer of zinc sulfide, containing ^{6}Li as the neutron absorbing agent, to convert the neutron signals into visible light photons. The photons are then led via a mirror onto a cooled 16-bit CCD camera.

2.1.4. Experimental procedure

Samples are brought to the experimental campaign site in a desiccator over a saturated potassium bromide solution (80% RH at 25 °C). Prior to each experiment, the conditioned sample is weighed and the thin thermocouples are cautiously inserted into the drilled holes. Then the sample is vapor sealed in thin Teflon tape and insulated with glass foam plates of 10 mm thickness, while the bottom and top surfaces are left exposed to air as shown in Fig. 3(c). Both Teflon and glass foam, containing no high attenuating elements, have minimum interaction with neutrons. The sample is then positioned in the xz-plane on the heating foil and held in place by a clamp and two vertical bolts. Three small metallic spacers provide a gap between the sample top and the horizontal clamp allowing moisture to leave the sample. Fig. 3(d) shows the experimental setup containing a sample, inside the neutron beamline.

An initial reference neutron image is acquired after the sample is fixed on the heating device. Then heating starts by a step rise of temperature to either 150 °C or 250 °C, which is maintained for 40 min. During this time, the images, i.e. two-dimensional projections of a three-dimensional object along the Z-ray beam

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