International Journal of Heat and Mass Transfer 55 (2012) 6211–6221

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Visualization and quantification of liquid water transport in softwood by means of neutron radiography

Marjan Sedighi-Gilani [a,*], Michele Griffa [a], David Mannes [b], Eberhard Lehmann [b], Jan Carmeliet [c], Dominique Derome [d]

[a] Laboratory for Building Science and Technology, Swiss Federal Laboratories for Materials Science and Technology (EMPA), Ueberlandstrasse 129, CH 8600 Dübendorf, Switzerland
[b] Paul Scherrer Institute (PSI), Villigen 5234, Switzerland
[c] Chair of Building Physics, Swiss Federal Institute of Technology Zurich (ETHZ), Wolfgang-Pauli-Strasse 15, CH 8093 Zürich Hönggerberg, Switzerland
[d] Swiss Federal Laboratory of Materials Research and Technology (EMPA), Ueberlandstrasse 129, CH 8600 Dübendorf, Switzerland

ARTICLE INFO

Article history:
Received 14 October 2011
Received in revised form 12 June 2012
Accepted 13 June 2012
Available online 12 July 2012

Keywords:
Hierarchical structure
Moisture content
Neutron radiography
Softwood
Swelling

ABSTRACT

Liquid water uptake in an orthotropic, cellular, hierarchical and natural material namely wood is investigated using neutron radiography. During water uptake in wood, liquid does not move up as a regular front as uptake rates differ in latewood and earlywood. In addition, moisture is adsorbed by the cell wall, resulting in a swelling that influences the process of moisture transport in wood. The high sensitivity of neutron to hydrogen atoms enables an accurate determination of the change in moisture content in the wood at the growth ring scale. The analysis of the spatial and temporal change of water content distribution shows that liquid water transport has different characteristics, depending on the direction of uptake and initial moisture content state.

Our results show that latewood cells play a more significant role in water uptake than earlywood cells and that ray tracheids also contribute to liquid transport. Latewood tracheids possess smaller cell lumens than earlywood cells that make them the preferential pathways for transport along the longitudinal direction. The process of liquid uptake is different in the radial and tangential directions as the path of the liquid is more intricate, involving also the rays and requiring more often traversing pits. In tangential direction, water uptake is occurring first in the latewood with a subsequent radial redistribution towards the earlywood. In radial direction, the growth ring boundary decreases the liquid transport rate, an indication that a significant portion of the rays are interrupted at that location. The moisture uptake rate in initially moist specimens is seen to be higher. Liquid transport leads to sorption and thus swelling of the specimens, which was dealt with by affine registration. Water uptake in wood cellular structure is a three-dimensional process that is controlled by the morphologic and sorption properties of the material at its different scales.

1. Introduction

Homogeneous porous materials, undergoing liquid uptake, show generally a uniform liquid front advancing proportionally with the square root of time, following Darcy law. For wood, an anomalous liquid uptake is observed where the square root of time relation becomes nonlinear [1]. During liquid uptake in wood, water does not move up in wood as a uniform front as the uptake rates differ in latewood and earlywood. In addition, moisture is adsorbed by the cell wall, resulting in the swelling of wood. Although macroscopic liquid water uptake in wood has been often studied [2–4], the respective role of the different components and features of wood hierarchical structure has been less addressed.

The occurrence of the different phenomena during liquid uptake at different time and spatial scales makes it impractical to explain the details of the liquid transport process from a simple liquid uptake experiment. Visualization of the liquid transport process in wood has thus been explored. Microscopy, optical or scanning electron, can be used to study the anatomy of wood in terms of liquid transport as in e.g. Kitin et al. [5] where pits between tracheids at the growth-ring boundaries are examined. Microscopy can also be used to document the traces of a staining liquid (e.g. safranine), for comparing radial and longitudinal liquid penetration depth [6], cured epoxy [7], or under vacuum-pressure impregnation [8]. The use of these visualization techniques allowed the later to identify that the main liquid flow pathways in wood are situated in the latewood longitudinal cells and to document the role of unaspirated bordered pits. However, the required destructive microtoming of the samples implies that microscopic studies

* Corresponding author. Tel.: +41 58 765 4871; fax: +41 58 765 4009.
E-mail address: marjan.gilani@empa.ch (M. Sedighi-Gilani).

0017-9310/$ - see front matter
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.06.045

Nomenclature

A	elemental molar mass [g/mol]
A_{cap}	capillary absorption coefficient [$kg/m^2s^{1/2}$]
E	energy of the incident neutrons [meV]
I	intensity of the neutron beam [$m^{-2}\ s^{-1}$]
$\tilde{I}$	intensity of the registered radiograph [$m^{-2}\ s^{-1}$]
N	atomic density [m^{-3}]
N_A	Avogadro constant [mol^{-1}]
RH	relative humidity [%]
t	time [s]
T	pixel-wise neutron beam transmission coefficient through the specimen
w	moisture content [kg/m^3]
X, Y	spatial coordinates [m]
z	thickness of the sample [m]

Greek symbols

$\varepsilon(E)$	energy sensitivity parameter for each pixel of the scintillator
Σ	neutron linear attenuation coefficient [m^{-1}]
ρ	material density [kg/m^3]
σ	microscopic cross-section interaction probability of an element with neutrons [m^2]
τ	water mass thickness [kg/m^2]

Subscripts

BB, DC, SS	black body, dark current & specimen scattering
h	uptaken water
ref	reference image
w	wood
0	initial state

take place after the uptake process. To capture the liquid flow in a time resolved way, a non-destructive means like X-ray projection has been used to document the process of liquid water transport in different isotropic sedimentary stones e.g. Cadoret et al. [9], Tidwell et al. [10], Roels and Carmeliet [11]. X-ray radiography in wood shows that the latewood growth rings are the preferential pathways for liquid water uptake [12]. Sandberg and Salin [13] used X-ray computer tomography (CT) to show that water rise is strongly uneven in longitudinal uptake, and depends upon the location of earlywood and latewood rings in the specimen. A main drawback of X-ray radiography is the limited resolution in quantifying the water content. Magnetic resonance imaging (MRI) is another imaging approach that has been used to visualize the spatial change of moisture content in wood [14–16]. Although spatial resolution reaches 78 m, the moisture resolution of MRI, while higher than X-ray radiography, lies between 2–4 kg/m^3 [15,16], thus may not capture small variations of moisture content.

Neutron radiography allows visualization of water spatial distribution and high resolution quantification of water content in porous media. It has been used for transport in fibrous thermal insulations [17], fuel cells [18,19], stone [20] and even analysis of boiling water [21]. Neutron radiography provides higher resolution for the determination of moisture content than MRI and X-ray radiography due to the high attenuation of the neutron beam by hydrogen nuclei, which are a main component of water. Thus, neutron radiography is highly suitable to investigate the transport and distribution of water in wood [22–24].

Water uptake in wood cellular structure is a three-dimensional process that is controlled by the morphologic and sorption properties of the material at its different scales. These variables cause the mechanism of liquid transport in radial, tangential and longitudinal directions to be different. Wood structure, for temperate softwood species, consists of the following four scales: cellular material, the cell, the growth ring and timber. The cell wall is a polymeric composite made of cellulose nanofibril aggregates immersed in a lignin/hemicellulose matrix. The sorption of water molecules in the cell wall result in the swelling of the cell wall and thus of wood at the macroscale. The organization of the cellulose aggregates explains the orthotropic mechanical and swelling behavior. At the cellular scale, wood consists mainly of longitudinal tracheid cells and radially oriented ray cells, the latter representing 5% of the wood volume. This cellular structure plays a main role in liquid water transport. Earlywood cells possess larger diameter and thinner walls than latewood tracheids. Fig. 1 shows tri-dimensionally the cellular structure of softwood (spruce), documented with high resolution synchrotron X-ray tomography. The lumens of the cells are connected by different types of openings: bordered pits between tracheids and different shaped cross-field pits between tracheids and ray cells. In earlywood, bordered pits are found on the radial cell walls, and rarely on tangential walls, while latewood in some species may present bordered pits on both radial and tangential cell walls [5,25]. Bordered pits are larger and more abundant on the radial cell walls of earlywood compared to latewood. During drying of wood, a valve-like occlusion of bordered pits, called aspiration [26], may occur and inhibit liquid transport between adjacent lumens, thus showing a dominant influence on the wood permeability. Cross-field zones are the wall areas intersecting ray cells and longitudinal tracheids. Cross-field zones are covered with pits, either small and slit-like holes, bordered or half bordered pits, depending to the wood species. Within a seasonal growth ring, the tracheid dimensions vary from earlywood cells with large lumens and thin walls, to thick-walled latewood cells of small lumen size. A better understanding of the role of the hierarchical structure on water transport in wood can be beneficial, for example, when improving impregnation and

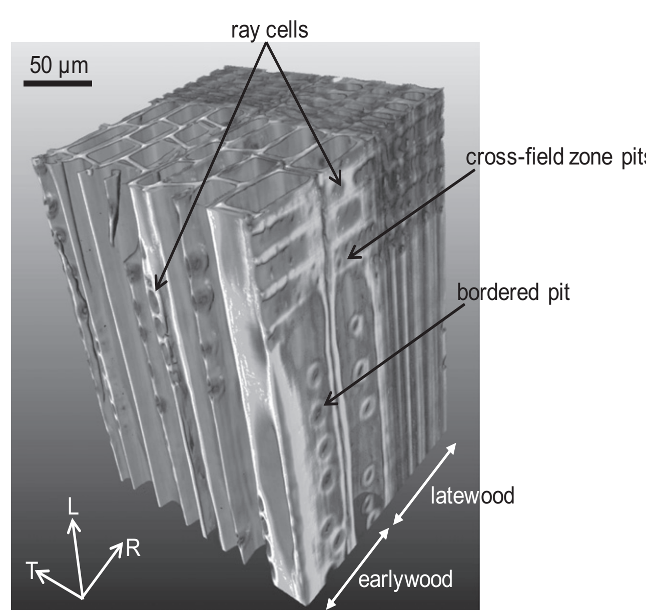

Fig. 1. Three-dimensional structure of softwood (Norway spruce) acquired by synchrotron X-ray tomography.