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# NMR imaging of fluid pathways during drainage of softwood in a pressure membrane chamber

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**Abstract**

An experiment was implemented to study fluid flow in a pressure media. This procedure successfully combines nuclear magnetic resonance imaging with a pressure membrane chamber in order to visualize the non-wetting and wetting fluid flows with controlled boundary conditions. A specially designed pressure membrane chamber, made of non-magnetic materials and able to withstand 4 MPa, was designed and built for this purpose. These two techniques were applied to the drainage of Douglas fir sapwood. In the study of the longitudinal flow, narrow drainage fingers are formed in the latewood zones. They follow the longitudinal direction of wood and spread throughout the sample length. These fingers then enlarge in the cross-section plane and coalesce until drainage reaches the whole latewood part. At the end of the experiments, when the drainage of liquid water in latewood is completed, just a few sites of percolation appear in earlywood zones. This difference is a result of the wood anatomical structure, where pits, the apertures that allow the sap to flow between wood cells, are more easily aspirated in earlywood than in latewood.


*Keywords:* NMR imaging; Pressure membrane; Porous media; Douglas fir; Multiphase flow; Percolation network

## 1. Introduction

To understand the mechanisms affecting the fluid flow in a porous media is very important for several applications such as drying and impregnation processes. Wood is a representative example of porous media, whose cellular structure is composed by a pore network joined by narrower connecting throats (pits). Softwood species have much greater uniformity than hardwoods. The principal structure of softwoods is the longitudinal tracheids, with approximately 92% of the volumetric composition. Tracheid size varies according to the species, the position in the tree and the kind of wood. In general, these elements have an average length of about 3500 μm and an average cross-sectional diameter of about 30 μm (Panshin and de Zeeuw, 1980). Due to wood physiology, tracheids formed during summer (latewood) have cell walls much thicker than those formed during spring (earlywood). Indeed, the double cell wall increases from about 4 μm in earlywood to more than 10 μm in latewood. This difference affects its physical and mechanical properties greatly. Tracheids are connected by bordered pits, which consist of two complementary gaps or recesses in the cell walls. These pits are covered with a membrane much thinner than the rest of the cell wall called the torus. The torus is surrounded by the annular margo consisting of microfibrillar strands with openings between them permitting the passage of liquids between the cells (Core et al., 1979; Panshin and de Zeeuw, 1980; Siau, 1995). If a gas/liquid interface passes through

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the pit, the capillary forces cause the membrane to move into the aspirated position, closing off the water flow. In the living tree, this feature exists to limit the damage due to cavitation in the sap column. In the case of wood as a material pit aspiration inhibits the liquid flow and is often problematic (drying and preservation).

Nuclear magnetic resonance imaging (MRI) is a non-destructive and a non-invasive technique that has been widely used to determine moisture distribution and fluid flow through a porous medium. For example, MRI has been used to study the flow through a porous medium in many fields including ground water hydrology, petroleum engineering, and soil science (Williams et al., 1991; Waggoner and Fukushima, 1996; Kimmich et al., 2001; Chen et al., 2002; Deurer et al., 2002). The majority of these works study the displacement of two immiscible fluids using a reference liquid and/or glass beads to simulate the porous medium. For example, Chen et al. (2002) used a model consisting of artificially consolidated sandstone saturated with oil. Oil in the model was flooded by an aqueous paramagnetic ion solution (500 mg $L^{-1}$ of $MnCl_2$) at a constant flux of 0.25 mL $min^{-1}$ and the distribution of the two phases at different stages of the water flooding was determined. A column filled with glass beads was used to study water flow in porous media by Deurer et al. (2002). In this study, water was pumped through the glass beads with a Pharmacia double syringe pump at rates of 125 and 250 mL $h^{-1}$.

Wood can be successfully imaged by MRI because of its relatively regular porous structure, in particular thanks to its almost self-similar structure obtained by a translation in the longitudinal direction. According to Araujo et al. (1993), NMR signal from green wood may be separated into three major components: solid wood, cell-wall water and lumen water. The transversal relaxation time ($T_2$) of solid wood decays rapidly to zero in tens of microseconds making it readily separable from the cell-wall water (bound water) signal, which has a $T_2$ from one to a few milliseconds. In contrast, the lumen water (liquid water) has a $T_2$ ranging from tens to hundreds of milliseconds (Riggin et al., 1979; Menon et al., 1987; Araujo et al., 1993; Almeida et al., 2007). Several works have used this technique to separate sapwood from heartwood, to differentiate growth rings and to visualise internal defects or anomalies of wood (Kuroda et al., 2006; Eberhardt et al., 2006). MRI was also used for non-invasive qualitative and quantitative studies of water distribution in wood and wood-drying kinetics (Quick et al., 1990; Meder et al., 2003; van Houts et al., 2004; Merela et al., 2005).

During experiment of fluid flow in porous media, the accurate control of the boundary conditions is a difficult task, especially at high humidity levels. The present work uses the pressure membrane principle to study the water flow in wood at high relative humidities. Although this method is mostly used on soil science (ASTM, 2000), it has been successfully used by many researchers in the studies of wood–water relationships (Robertson, 1965; Stone and Scallan, 1967; Griffin, 1977; Fortin, 1979; Almeida and Hernández, 2006).

The present work combines MRI with an accurate method to control the drainage inside a porous medium (Douglas fir). This combination permits the displacement of the wetting phase by an overpressure of the non-wetting phase to be observed. The 3D images of the moisture content fields versus time provide new insights into fluid migration mechanisms taking place in softwood: cluster formation, coalescence of cluster, absence of liquid migration in earlywood. To our knowledge, this is the first time that these phenomena have been observed by non-destructive methods and with the rigorous control of drainage conditions.

## 2. Materials and methods

The study was carried out in 21-year-old Douglas fir (*Pseudotsuga menziesii*). Douglas fir sapwood samples were cut from a green log. Longitudinal and radial specimens were turned using a lathe (Fig. 1A). A diamond wire saw (Well model 3241, ESCIL) was used to cut the cylindrical samples. The final dimensions of the longitudinal specimens were 17 mm in diameter and 20 mm in length (parallel to the longitudinal tracheids) and for the radial ones 17 mm in diameter and 15 mm in length (parallel to the radial elements). In order to maintain the green state until the test, the samples were soaked in distilled water for no more than 10 days. The test material had an average basic wood density (oven-dry mass to green volume) of 467 kg $m^{-3}$ (coefficient of variation (CV) of 5%).

### 2.1. Experiments

#### 2.1.1. Pressure membrane principle

The pressure membrane principle is used to control the water state in a porous medium at high humidity levels (>95% RH) or to apply a pressure difference between the wetting phase and the non-wetting phase. This principle lies in the concept of water potential ($\psi$), which is derived from classical thermodynamics and defined as the difference between the specific Gibbs free energy of water in the state under study and in a standard reference state (Siau, 1995). The reference state generally used is a hypothetical pool of pure free water at atmospheric pressure, at a given elevation and at the same temperature as that of the water in the porous material (Fortin, 1979). The water potential is normally expressed in terms of energy per unit mass in J $kg^{-1}$. The water potential of moist air may be deduced from Kelvin's law.

$$\psi = \frac{RT \ln h}{M_w} \quad (1)$$

where $R$ is the gas constant (8.31 J $mol^{-1}$ $K^{-1}$); $T$ is the absolute temperature (K); $h$ is the relative vapor pressure and $M_w$ is the molar mass of water ($18 \times 10^{-3}$ kg $mol^{-1}$).