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Thermal conductivity measurements on wood materials with transient plane source technique

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ABSTRACT

The conductive heat flux can be modeled by a vector: in a real anisotropic material, the contribution of each directional components is not easy to measure. The transient plane source technique, also known as Hot-Disk, stands as a valid device for the measurement of thermal diffusivity in this kind of materials if some geometric requirements are met for the preparation of the samples. In this paper, the theoretical derivation of the equation ruling the computation of the thermal diffusivity and conductivity in anisotropic material using the Hot-Disk device is presented and used for obtaining these properties for three tree species from the Northeast of Italy: oak, spruce and larch.

1. Introduction

Thermal characterization of building materials is a current issue of interest, especially given the increasing concern about energy efficiency and thermal performance of buildings, both new and existing, worldwide. What is more, recent advances in sustainable housing are leading to the use of natural materials, especially wood, as it is a widely available material and presents lower thermal conductivity values than other construction materials: aluminum (160 $\mathrm{W\,m^{-1}\,K^{-1}}$), stones (2.2 $\mathrm{W\,m^{-1}\,K^{-1}}$ for slate, 2.8 $\mathrm{W\,m^{-1}\,K^{-1}}$ for granite) and glass (1.4 $\mathrm{W\,m^{-1}\,K^{-1}}$), among others [1–3]. However, nowadays, the wooden products existing in the market barely provide any data regarding their thermal behavior, so it is difficult for users to choose among different types of wood using different criteria than color. Therefore, a thermal characterization of different types of wood would imply an important advance towards the standardization of the wooden market and the consideration of energy requirements by the users.

Wood is an anisotropic material as a consequence of its structure constituted of vertical elongated cells whose walls are built up with long-chain linear polymers (cellulose) arranged in bundles called microfibrils aligned with the longitudinal axis of the cell [4]. This fact makes possible the measurement of the properties of wood in three conditions: longitudinal direction parallel to the grain, radial and tangential to the annual accretion rings directions. Steinhagen [5] showed that the orientation of the molecular chains gives a thermal conductivity greater in the longitudinal direction (parallel to grain) than in the tangential direction.

Given its anisotropic nature and the number of parameters of influence, the calculation and measurement of the thermophysical properties of wood is a challenging task widely addressed by the scientific community. There are data on thermal properties of different kinds of wood available, and various authors suggested equations for the evaluation of the influence of temperature, moisture and density on the thermal properties of wood [6]. However, an extended survey reveals a lack of experimental data on thermal conductivity of wood species grown in Italy.

In most thermal conductivity studies published on wood, the steady state hot-plate apparatus is used for the determination of conductivity [9] as reference. More recently, Faouel performed the measurement of the three components of thermal conductivity (radial, tangential and axial) in different wood species using also photothermal techniques [7] and the transient hot-bridge method [8] for different moisture contents.

An alternative transient technique for the measurement of thermal conductivity, the Hot-Disk technique, appeared in 1991

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[10] as a special case of the transient plane source technique, in which the sensor is a plane disk consisting on a number of concentric rings. This method has gained popularity due to its accuracy and speed, and to the fact that it can be used to measure thermal conductivity in a wide range of materials: bulk and anisotropic; solid, gel and liquid; using both thick and thin samples [11–14]. This fact has led to the appearance of this technique as a standardized technique for the thermal characterization of materials [15].

The Hot-Disk sensor acts both as a current supplier and as a temperature monitor, being sandwiched between two samples during the experiment. This way, apart from supplying the small constant current that produces the heat input, the sensor also determines accurately the temperature increase through resistance measurement. This temperature increase is highly dependent on the thermal transport properties of the material surrounding the sensor. By monitoring this temperature increase over a short period after the start of the experiment, it is possible to obtain precise information on thermal transport properties. Deeper explanation can be found in [16].

In the case of anisotropic materials, the Hot-Disk can be used if a number of requirements established by the configuration of the system and the heat model assumed are met. There must be only three main directions of heat transfer forming an orthogonal system, and thermal properties can vary only in one of these three directions, being equal through two of them [15]. In other words, the Hot-Disk technique can only be applied to orthotropic materials in which the thermal properties are homogeneous in one plane. Consequently, regarding wood, special attention should be paid to the cut of the samples so that they fulfill the previous conditions.

Since wood is a hygroscopic material it will always contain water. The amount of water has a profound influence on almost all properties of wood, as it does for the thermal properties. Thus, it is of great importance that the values of the properties determined are given together with the associated moisture content. In this paper, the thermal characteristics of the different tree samples were measured in dry conditions (oven dry) and at room temperature around 20 °C, in order to avoid the influence of water in the thermal properties measured.

The purpose of this study is first to present the theoretical background of the measurement of thermal properties in anisotropic (orthotropic) materials with the Hot-Disk, and validate its performance through the measurement of the thermal properties of some wood species grown in the Northeast part of Italy. The analyzed wood samples are from softwood (spruce – *Picea abies*, larch – *Larix deciduas*), and from hardwood (oak – *Quercus robur*)[1]. After the density determination, specific heat and thermal conductivity and diffusivity (both in the radial and the axial directions) are obtained applying different characterization techniques.

This paper is organized as follows. This section presents the state of the art and motivation of the research. The theoretical background of the measurement in orthotropic materials is discussed in Section 2. Section 3 includes the results of the application of the ruling equation of the Hot-Disk measurement in anisotropic materials to the thermal characterization of three different wood species: spruce, larch and oak. Section 4 presents a discussion on the results, and finally Section 5 consists on the conclusions achieved after the use of the Hot-Disk technique for the thermal characterization of wood.

2. Theory

The result of the average temperature increase in the Hot-Disk sensor in anisotropic materials has already been presented [11], but the detailed mathematical derivation, as included in this paper, was not present in literature.

Media with thermal properties that are dependent on the direction (anisotropy) are characterized by the heat flux direction that is not necessarily normal to the isothermal surfaces. In this case, the heat flux components are a linear combination of the temperature gradient components by a thermal conductivity matrix (a second order tensor) according to the following equation (Fourier Law):

$$\mathbf{q} = -\Lambda \times \nabla T \Leftrightarrow \left(q_x, q_y, q_z\right) = -\begin{pmatrix} \lambda_{xx} & \lambda_{xy} & \lambda_{xz} \\ \lambda_{yx} & \lambda_{yy} & \lambda_{yz} \\ \lambda_{zx} & \lambda_{zy} & \lambda_{zz} \end{pmatrix} \begin{pmatrix} \dfrac{\partial T}{\partial x} \\ \dfrac{\partial T}{\partial y} \\ \dfrac{\partial T}{\partial z} \end{pmatrix} \tag{1}$$

where $\boldsymbol{q} = (q_x, q_y, q_z)$ is the heat flux vector, $\nabla T = (\partial T/\partial x, \partial T/\partial y, \partial T/\partial z)$ is the temperature gradient (a vector as well) and Λ is the conductivity tensor, a 3×3 symmetric matrix. Λ is potentially dependent on the position, time and temperature, but we will not consider these possibilities in what follows.

The conductivity tensor can be significantly simplified in presence of spatial symmetries. The Hot-Disk sensor is able to discriminate between radial (along the radius of the concentric circles of the probe wires) and axial (perpendicular to the probe plane) conductivities: the mathematical description of the Fourier law with cylindrical coordinates allows an easier modeling of the Hot-Disk probe. Orthotropic systems (characterized by three different thermal conductivity along three orthogonal directions) with isotropic conductivity in the plane of the hot disk (radial) and different from the one perpendicular to plane (axial) can be described as follows:

$$\left(q_x, q_y, q_z\right) = -\begin{pmatrix} \lambda_r & 0 & 0 \\ 0 & \lambda_r & 0 \\ 0 & 0 & \lambda_a \end{pmatrix} \begin{pmatrix} \dfrac{\partial T}{\partial x} \\ \dfrac{\partial T}{\partial y} \\ \dfrac{\partial T}{\partial z} \end{pmatrix} \tag{2}$$

where λ_r and λ_a are the radial and axial thermal conductivity, respectively. By introducing the continuity equation:

$$\nabla \times \mathbf{q} + \rho c \frac{\partial T}{\partial t} = 0 \tag{3}$$

where ρ is density and c the specific heat, the differential equation of heat conduction is finally obtained:

$$\lambda_r \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \lambda_a \frac{\partial^2 T}{\partial z^2} - \rho c \frac{\partial T}{\partial t} = -Q \tag{4}$$

On the right part of the equation, a source appears producing Q joule of heat per unit of time and volume. Q is in general a function of the spatial coordinates and time as well.

According to [17,18], Eq. (4) is solved by the following fundamental Green's function that can be considered as the temperature due to an instantaneous point source of strength ρc released at point (x', y', z') at time t':

$$\begin{aligned} G(x,y,z,t|x',y',z',t') &= \frac{(\rho c)^{3/2}}{8(\pi^3 (t-t')^3 \lambda_r^2 \lambda_z)^{1/2}} e^{-\frac{\rho c}{4(t-t')}\left[\frac{(x-x')^2}{\lambda_r} + \frac{(y-y')^2}{\lambda_r} + \frac{(z-z')^2}{\lambda_a}\right]} \\ &= \frac{1}{8(\pi^3 (t-t')^3 \alpha_r^2 \alpha_a)^{1/2}} e^{-\frac{1}{4(t-t')}\left[\frac{(x-x')^2}{\alpha_r} + \frac{(y-y')^2}{\alpha_r} + \frac{(z-z')^2}{\alpha_a}\right]} \end{aligned} \tag{5}$$

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[1] **Softwood** is a generic term used in woodworking and the lumber industries for wood from conifers. The term softwood designates wood from gymnosperm trees (plants having seeds with no covering). The term **hardwood** designates wood from broad-leaved (mostly deciduous) or angiosperm trees (plants that produce seeds with some sort of covering).