Thermal properties of wood: measurements by transient plane source method in dry and wet conditions

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Abstract. Increasing use of wooden material in new constructions and retrofit activities push to a deeper comprehension of properties and specifically thermal properties of different wood species. On one side wooden products on the market are accompanied by few and generic information on the other side analysis of literature confirms a lack of experimental data on thermal conductivity of wood species grown in Italy. In this paper some species of softwood like spruce and larch, and hardwood, like elm, oak and ash are analysed and their thermal conductivities as a function of the equilibrium water content are evaluated by the use of a transient plane source. Results are in line with literature values and, in general, conductivity augments with water content increasing. The relationship between water content and conductivity exploited a linear behaviour for all species.

1. Introduction

Thermal characterization of wood is a current issue of interest in Europe and Italy, especially as a consequence of the increasing use of this material in new constructions and retrofit activities. Given the concern about energy efficiency and thermal performance of buildings, wood presents a moderately low thermal conductivity and in fact it is a natural material that is readily available with low environmental impacts.

However, on the market the wooden products are accompanied by few and generic information regarding their thermal performance, so it is difficult for users to choose among different species. An extended analysis of technical literature confirms the availability of data on thermal properties of different kinds of wood and equations for the evaluation of the influence of temperature, moisture and density on the thermal properties of wood, but also a lack of experimental data on thermal conductivity of wood species grown in Italy [1, 2]. Therefore, a thermal characterization of Italian different types of wood can be useful.

In fact wood is a hygroscopic material and presents an equilibrium humidity content dependent from the relative humidity and temperature of air in which it is immersed. 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 previous works authors presented the thermal properties of some wood species grown in the Northeast part of Italy at dry conditions [3, 4]. In this paper, the influence of water on thermal conductivity is considered, both for samples of softwood, like spruce and, larch, and hardwood, like elm, oak and, ash.
2. Measurement method

In most thermal conductivity studies published on wood, the steady state hot-plate apparatus is used for the determination of conductivity [5,6] as a reference; an alternative technique for this measurement is the Hot-Disk technique, introduced in 1991 as a special case of the transient plane source technique [7]. The sensor is a thin, plane disk consisting on a metallic wire (generally platinum) wound as a spiral with several concentric turns. Being electrically conductive, the sensor is generally enveloped in a thin case of Kapton or Mica, that are both dielectric materials and good thermal conductors. This method has gained popularity due to its accuracy and speed, and to the fact that it can be used for the characterization of a wide range of materials: bulk and anisotropic; solid, gel and liquid; using both thick and thin samples [8]. In his way this technique has become a standardized technique for the thermal characterization of materials [9].

The Hot-Disk sensor acts both as a source of heat by Joule effect and as a temperature probe (much like a Platinum Resistance Thermometer), 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 [4,10].

In this study the TPS 2500S device produced by Hot Disk AB was used. It is a general-purpose R&D thermal conductivity meter and meets indications of ISO 22007-2 standard [9]. Its characteristics are described in the following (Fig. 1). A Kapton sensor with a 14.61 mm beam type 4922 was used, two samples were used, as identical as possible with the hot disk sensor placed in between.

- Thermal conductivity: 0.005 a 500 W m$^{-1}$ K$^{-1}$
- Thermal diffusivity: 0.1 to 100 mm$^{2}$ s$^{-1}$
- Specific heat : Up to 5 MJ m$^{-3}$ K$^{-1}$
- Measurement time: 1 - 1280 s
- Reproducibility: 1%
- Accuracy: 5%
- Sensor type: Kapton insulated (temperature to 180$^\circ$C), Mica insulated (temperature to 750$^\circ$C).

Figure. 1. Hot-Disk measurement apparatus and characteristics. The sensor is sandwiched between two specimens of the same wood specie with the same orientation.
In a previous work (Laguela et al. [3]), the authors analysed thoroughly the physics underlining the Hot Disk equipment, extending the analysis for bulk isotropical samples made by He [10] to the case of materials with orthotropic thermal conductivity tensor. Following that analysis, the authors implemented the relevant equations in MATLAB® language. The extraction of the parameters is done by an optimization procedure that minimizes the difference between experimental data and model data according to the least square criterion. Being the equations non-linear in the parameters of interest, the optimization procedure iteratively search a minimum in the parameters space according to the Levemberg-Marquardt algorithm. Therefore, the anisotropy module implemented in the TPS 2500S system was not utilized, preferring instead the home-made procedure.

Five different wood species grown in Italy were chosen for the analysis: oak, elm, ash, spruce and larch. These are chosen as representative of the different kinds of wood: oak, elm and ash are hardwood, while spruce and larch are classified as softwood. Between the two of them, spruce is an evergreen coniferous, whereas larch is deciduous with hard mechanical properties. The selected samples were obtained from wood log without cracks, notches and impurities. Specimens were prepared by planning the board surfaces and sawing them into cubes with nominal dimension 50 mm x 50 mm x 50 mm. The preparation was made in such way that they permitted the measurement of the thermal conductivity along three orthogonal directions (Fig. 2), even though not necessarily the principal ones. Indeed, wood is an anisotropic material, both from the mechanical and thermal point of view. This is due to its structure that is constituted of vertically elongated cells whose walls are made of long chain cellulose arranged in bundles called microfibrils aligned with the longitudinal axis of the cell. The test specimens were obtained from the sapwood region and were cut from successive portions of the same stem to obtain as many identical and uniform characteristics as possible.

![Image of wood samples](image)

Figure 2. Samples of wood used for measurements with the Hot-Disk. The cut and cubic shape allow to test the wood in different directions of the conductivity tensor.

As a first step the dry properties of each wood species are measured. Three couples of oven-dry specimens were prepared, so that sufficient representation of mean direction of grain, density and other physical characteristics can be obtained. As described by Siau [11], oven-dry samples were obtained using a drying temperature of 105°C for a sufficiently long time until a constant mass of the sample was obtained. After heating at such temperature, both the free and bound water in wood was released, and the specimens were completely dry. To preserve from any moisture undesirable gain or loss, all of the treated specimens were stored in sealed plastic boxes until measurement.

Dimension measurements were performed with a micrometer, with 0.01mm resolution and 0.02mm accuracy; weight of the samples was measured with a 0.1 mg resolution balance. Consequently, the average values of apparent oven-dry densities of the samples were calculated for each sample based on oven-dry masses and volumes.

Moreover, wood is a porous material and its porosity affects the density and thermal conductivity, much less or not at all the specific heat according to [4]. Porosity $r$ was estimated using the following equation:

$$ r = 1 - \left( \frac{\rho_{ave}}{\rho_{th}} \right) $$

(1)
where $\rho_{\text{ave}}$ is the average apparent density of the sample and $\rho_{\text{th}}$ is the assumed theoretical density of a compact solid wood free from voids. Its value is assumed to be 1500 kg m$^{-3}$ [12]. Results obtained after the measurement of density for the five types of wood are shown in Table 1, as well as the corresponding values of porosity. Since density is measured for wood in oven-dry conditions, it is linearly related with porosity, the higher the porosity, the lower the density.

| Dry Density (kg m$^{-3}$) | Oak  | Fir   | Larch | Elm  | Ash  |
|--------------------------|------|-------|-------|------|------|
|                          | 757.8| 341.5 | 505.7 | 597.7| 608.2|

| Porosity   |
|------------|
| 0.49       |

Table 1. Density and porosity measured for the samples of the different specimens of wood in oven-dry conditions.

After dry characterization we have gone on to study the influence of equilibrium humidity on wood thermal properties. The samples were exposed to constant temperature and humidity for 10 days. Constant temperature was obtained using a climatic chamber, while the desired humidity values were obtained using salt solutions usually applied in calibration of humidity sensors. Samples inside plastic boxes containing saturated salt solutions were positioned inside the climatic chamber. Testing temperature chosen was 20°C and relative humidity choices for the verification were 33%, 54%, 75%. The relative humidity values were obtained respectively with saturated salt solutions using MgCl$_2$, Mg(NO$_3$)$_2$ and NaCl. The equilibrium humidity percentage in wood specimens are reported in table 2.

| wood type | equilibrium air 33% RU | equilibrium air 54 % RU | equilibrium air 75 % RU |
|-----------|-------------------------|-------------------------|-------------------------|
| Fir       | 3,9%                    | 6,9%                    | 10,9%                   |
| Larch     | 4,4%                    | 7,0%                    | 9,3%                    |
| Elm       | 5,0%                    | 7,4%                    | 10,3%                   |
| Ash       | 2,3%                    | 7,1%                    | 9,6%                    |
| Oak       | 1,9%                    | 4,3%                    | 7,1%                    |

Table 2. Water percentage measured for the samples of the different specimens of wood in equilibrium with various air relative humidity.

3. Results

Being wood an anisotropic material, it presents different behavior to heat transfer in three main directions: parallel, perpendicular and tangential to the fibers, denoted here as axial, radial and tangential direction (figure 3). The cut and cubic shape of the samples allow to test the wood in different directions of the conductivity tensor. The experiments were performed with low power and long measurement time given the a-priori knowledge of the low thermal conductivity, and hence diffusivity, of wood. Therefore, 0.1 W and 320 s were the parameters of each measurement. Ambient conditions were 20°C and 30% humidity. Taking into account the fact that the sensor has to be sandwiched between two samples during the experiment, and in order to have good error estimation, 3
pairs of samples were used for each wood species. Therefore, at least 9 measurements were carried out for each wood species, with an average time between consecutive measurements of 30 min, for the attainment of the steady state of each new configuration. Being the time for a significant moisture content variation of the order of four to five hours (consider that the equilibrium at each moisture content takes several days), during the measurement time the moisture content of the samples can be considered constant.

**Figure 3.** Sample of wood used for measurements with the Hot-Disk. The cut and cubic shape allow to test the wood in different directions indicated as reported.

| equilibrium RU | Ash | Elm |
|----------------|-----|-----|
|                | axial | radial | tangential | axial | radial | tangential |
| 0%             | 0,243 | 0,2  | 0,206 | 0,224 | 0,18 | 0,177 |
| 33%            | 0,261 | 0,217 | 0,217 | 0,235 | 0,185 | 0,191 |
| 54%            | 0,266 | 0,217 | 0,228 | 0,248 | 0,198 | 0,198 |
| 75%            | 0,276 | 0,226 | 0,238 | 0,257 | 0,202 | 0,207 |
| Fir            |      |      |      |      |      |      |
| 0%             | 0,15 | 0,102 | 0,116 | 0,212 | 0,151 | 0,161 |
| 33%            | 0,161 | 0,113 | 0,129 | 0,225 | 0,172 | 0,172 |
| 54%            | 0,166 | 0,126 | 0,144 | 0,232 | 0,179 | 0,174 |
| 75%            | 0,174 | 0,135 | 0,155 | 0,235 | 0,196 | 0,187 |
| Larch          |      |      |      |      |      |      |
| 0%             | 0,311 | 0,231 | 0,243 |      |      |      |
| 33%            | 0,318 | 0,241 | 0,245 |      |      |      |
| 54%            | 0,323 | 0,244 | 0,25  |      |      |      |
| 75%            | 0,326 | 0,252 | 0,261 |      |      |      |

**Table 3.** Results of the conductivity measurements [W m⁻¹ K⁻¹] performed with the Hot-Disk.

Results for the five wood species under study are shown in Table 3, where the axial conductivity corresponds as much as possible to the "along fiber", tangential corresponds as much as possible to
"tangential to fiber" and radial corresponds as much as possible to "through the fiber" directions of the heat flux. We can deduce the following trends:

- In general the highest values of conductivity is obtained on the most dense species: in order oak, ash, elm, larch and fir;
- For all species and with different water content the conductivity measured along the fibers is higher than the radial and tangential conductivities;
- For all species the increase in moisture content increases the value of conductivity;
- The increase of conductivity at the increasing wood density is slightly less steep.

Conductivity along grain for all species is presented in figure 4. The oak presents the highest values and fir presents the lowest values coherently with their densities. Ash, elm and larch present similar behaviors. The obtained conductivities are comparable with values found in literature [13] [14] [15], [16].. [17], [18]). (table 4) even though, in general, the value measured in the present study are slightly higher. With perpendicular conductivity is described a mean value of radial and tangential conductivity.

![Figure 4. Behavior of conductivity values along fibers for all wood species as a function of water content.](image)

| Parameter               | Oak  | Fir  | Larch | Elm  | Ash  |
|-------------------------|------|------|-------|------|------|
| Perpendicular Conductivity W/m K⁻¹ | 0.16 | 0.09 | 0.10  | 0.16 | 0.18 |
| Axial Conductivity      W/m K⁻¹   | 0.30 | 0.14 | 0.14  | 0.22 | 0.23 |

Table 4. Values of the thermophysical properties found in literature for wood species under study.
4. Conclusions
This paper presents the result of a measurement campaign of thermal conductivity of different wood species grown in the Northeast of Italy: oak, ash, fir, elm and larch. First of all, the samples were oven-dry to remove all humidity from their interior, and consequently to avoid all the influences of humidity in the measured values. After that, the samples were exposed to humid air with three values of RU. Equilibrium condition for wood specimens were considered. Results are in line with literature values and, in general, conductivity augments with water content increasing. The relationship between water content and conductivity results linear for all species. The study can be completed considering some other species as cherry, pine, beech, used by construction and furniture industry. Moreover the measurements of specific heat and thermal diffusivity are planned.

5. References
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