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Wood Thermal Properties

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Abstract

Wood thermal properties specify the answers to the questions related to heat transfer. The values of specific heat, thermal conductivity, and thermal diffusivity were simultaneously determined with quasistationary method. Wood is distinguished as a natural material for accumulating the energy by heat transfer, as isolating material, with the ability to slowly equilibrate its different temperatures. The measured thermal properties value of beech and fir wood samples support those conclusions. Known dependences of wood thermal properties on anatomical direction, density at given moisture content, temperature are modelled and incorporated into heat conduction equation to provide base for next evaluation of measured data. The heat conduction solutions, based on known wood thermal properties, are used in similar problems. It is shown that thermal properties influence the surface equilibrium temperature between skin and wooden sample and the solution of heat conduction equation describes the flux passing through the log as an element of log-cabin house. Also thermal diffusivity is a component of equation that determines the position of observed point of wood during conduction. The results served as a base point for planning the experiments, for designing the processes of heat transfer, for designing the furniture and wooden houses, for designing the machines and equipment in woodworking industry and others.

Keywords: wood, specific heat, thermal conductivity, thermal diffusivity, coefficient of thermal expansion

1. Introduction

The desired change of wood temperature is involved in wood processing such as drying, forming, gluing, finishing and others. Also, suitable temperature is a part of comfortable environment in wooden houses. The heat transfer is one of the processes how to change the temperature of wood. Wood is surrounded by boundary from its surrounding. Heat transfer occurs spontaneously through the boundary solely due to the non-zero difference in temperature of wood and its surrounding. The processes by which the heat is transferred are classified into three categories: conduction, convection and radiation. The mechanism of conduction is dominant

process of heat transfer through wood in many previously mentioned situations of wood processing. The convection and radiation are also included in description of heat transfer through wood, mainly in the form of boundary conditions. The basic condition for convection is moving medium. Relative motion of wood and surrounding occurs in convective boundary condition. Also, permeable wood transfers simultaneously work and heat (outside pressure and temperature as potential). Such mechanism produces deviation from results of conduction.

We are solving three basic questions related to heat transfer by wood:

1. How much heat is needed for changing the wood temperature by 1 K?

2. How much heat is flowing through the wall?

3. How fast two different temperatures in wood equilibrate?

The aim of the chapter is to answer to these questions. The first question is related to specific heat capacity, the second question is related to thermal conductivity and the third one to thermal diffusivity. The differences in wood temperature at constant pressure causes wood dimensional changes. The question about wood dimension after wood temperature change is related to thermal expansion coefficient. However, this question is often omitted because small value of thermal expansion coefficient in comparison with coefficient of swelling or shrinking. All the mentioned quantities are measured for wood. The quantities definitions are independent from different measuring methods, but often assign quantities values with appropriate units do not keep such clearness. Therefore, the next part of chapter is devoted to measuring method of wood thermal properties.

2. Research method and results

Heat, internal energy, entropy are hardly measured quantities [1]. But temperature, length, mass and time are easy measureable. Therefore, heat is computed from easier measured quantities, for example, temperature difference and others. Let wood be a system of conserving the enthalpy H:

$$H = U + pV \tag{1}$$

where U is internal energy, p is pressure, V is volume of wood. The next equation expresses continuity for enthalpy:

$$\frac{\partial H}{\partial t} + \frac{\partial q}{\partial x} = 0 \tag{2}$$

where q is heat flux, t is time and x is dimensional coordinate. After applying the first thermodynamic principle to equation of enthalpy change, it follows:

$$\Delta H = Q - W' + \Delta(pV) = mc_p\Delta T + V\Delta p = (\rho c_p \Delta T + \Delta p)V \tag{3}$$

where Q is heat, W' is work carried out by wood on surrounding, m is wood mass, c_p is wood mass specific heat capacity at constant pressure, ΔT is temperature difference in wood. Specific

heat is the amount of heat transferred to unit mass of wood to rise its temperature by 1 K. Specific heat is property by which we are able to distinguish wood as a good material for accumulate the energy by heat transfer. The flux which changes the enthalpy is divided into two parts: flux which is related to change of temperature q_U, and flux which is related to change of pressure q_W inside arbitrary wood infinitesimal volume dV:

$$\left(\rho c_P \frac{\partial T}{\partial t} + \frac{\partial q_U}{\partial x}\right) dV = 0 \tag{4}$$

$$\left(\frac{\partial p}{\partial t} + \frac{\partial q_W}{\partial x}\right) dV = 0 \tag{5}$$

where ϱ is wood density. The sum of both previous equations gives zero sources of enthalpy in wood volume. Both equations are valid for arbitrary volume and, moreover, there is need to determine the flux of internal energy as temperature function.

It follows from observation, that temperature difference in space spontaneously produces the heat rate from higher to smaller values of temperature. The heat rate Q/t is proportional to temperature difference ΔT, to the area of heat transfer S and inversely proportional to the distance in space d. These findings are summarized by Fourier law:

$$\frac{Q}{St} = \lambda \frac{\Delta T}{d} \tag{6}$$

where λ is thermal conductivity and represents the wood property to conduct heat. Thermal conductivity is property by which we are able to distinguish wood as heat insulator or pure heat conductor. The differential form of Fourier law:

$$\vec{q} = -\overline{\overline{\lambda}} \, grad(T) \tag{7}$$

relates the heat flux q and the gradient of temperature. In general, vector of heat flux and temperature gradient are not at one line, therefore, thermal conductivity is the second order tensor. Its eigenvalues are positive numbers in $Wm^{-1} K^{-1}$. The minus sign in Eq. (7) expresses the increase of the wood temperature by the heat flux directed to its volume, which surface is oriented outside the volume. We have always made sure with measurement that thermal conductivity is symmetric tensor and; moreover, for wood, it is possible to arrange it to diagonal form according to suitable transformation. The form of Fourier law for radial slab is:

$$\begin{pmatrix} q_z \\ q_x \\ q_y \end{pmatrix} = - \begin{pmatrix} \lambda_L & 0 & 0 \\ 0 & \lambda_R & 0 \\ 0 & 0 & \lambda_T \end{pmatrix} \begin{pmatrix} \dfrac{\partial T}{\partial z} \\ \dfrac{\partial T}{\partial x} \\ \dfrac{\partial T}{\partial y} \end{pmatrix} \tag{8}$$

where wood anatomical directions (L—longitudinal, R—radial, T—tangential) coincide with orientation of Cartesian coordinate axis (z, x, y). Radial board is linear orthotropic material.

The form of Fourier law for tangential slab is formulated:

$$
\begin{pmatrix} q_z \\ q_x \\ q_y \end{pmatrix} = - \begin{pmatrix} \lambda_L & 0 & 0 \\ 0 & \lambda_R \dfrac{x^2}{x^2+y^2} + \lambda_T \dfrac{y^2}{x^2+y^2} & (\lambda_R - \lambda_T)\dfrac{xy}{x^2+y^2} \\ 0 & (\lambda_R - \lambda_T)\dfrac{xy}{x^2+y^2} & \lambda_T \dfrac{x^2}{x^2+y^2} + \lambda_R \dfrac{y^2}{x^2+y^2} \end{pmatrix} \begin{pmatrix} \dfrac{\partial T}{\partial z} \\ \dfrac{\partial T}{\partial x} \\ \dfrac{\partial T}{\partial y} \end{pmatrix}
\tag{9}
$$

Fourier law for log is suitable to express in cylindrical coordinates (z, r, ϕ) = (L, R, T):

$$
\begin{pmatrix} q_z \\ q_r \\ q_\varphi \end{pmatrix} = - \begin{pmatrix} \lambda_z & 0 & 0 \\ 0 & \lambda_r & 0 \\ 0 & 0 & \lambda_\varphi \end{pmatrix} \begin{pmatrix} \dfrac{\partial T}{\partial z} \\ \dfrac{\partial T}{\partial r} \\ \dfrac{\partial T}{r\partial \varphi} \end{pmatrix}
\tag{10}
$$

The log is cylindrical orthotropic material. Fourier law (7) does not contain time of the process explicitly. The coupling of Fourier's law and Eq. (4) results in heat conduction equation:

$$
\mathrm{div}(\overline{\overline{\lambda}}\,\mathrm{grad}(T)) + s = c_p \rho \frac{\partial T}{\partial t}
\tag{11}
$$

s denotes the rate of energy release or its consumption in volume unit of internal sources or sinks. As wood can be distinguished as cylindrical orthotropic material [2–4] or as its special case linear orthotropic material, heat conduction equation has the form with constant eigenvalues of thermal diffusivity α:

$$
\frac{\alpha_R}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r}\right) + \frac{\alpha_T}{r^2} \frac{\partial^2 T}{\partial \varphi^2} + \alpha_L \frac{\partial^2 T}{\partial z^2} = \frac{\partial T}{\partial t}
\tag{12}
$$

in cylindrical coordinate system as wood has the form of log or:

$$
\alpha_R \frac{\partial^2 T}{\partial x^2} + \alpha_T \frac{\partial^2 T}{\partial y^2} + \alpha_L \frac{\partial^2 T}{\partial z^2} = \frac{\partial T}{\partial t}
\tag{13}
$$

in Cartesian system as wood has the form of radial slab. Thermal diffusivity is the ratio of thermal conductivity and product of mass specific heat capacity and density at given moisture content. Thermal diffusivity is property by which we are able to distinguish that wood equilibrates its different temperatures slowly. Also, it describes the slowest temperature change in wooden body. The solution of heat conduction equation provides the temperature field in wood (direct problem) and the base of measurement method of thermal properties (inverse problem). Advantage of solutions is possibility to describe the similar examples of heat transfer by conduction. The various techniques (analytical or numerical) are employed to solve heat conduction equation. Both of them have the same feature of using initial and boundary conditions to compute particular solution. The initial and boundary conditions should match

the situation as best as possible. The initial condition describes the temperature field in wood at the beginning of the situation. There is possibility to recognize three kinds of boundary conditions or their combination [5, 6]:

the 1st (I.) kind boundary condition describes the surface temperature as a function of time (Dirichlet condition),

the 2nd (II.) kind boundary condition describes the heat flux at the surface as a function of time (Newman condition),

the 3rd (III.) kind boundary condition describes the heat flux at the surface as a function of surface temperature (Robin condition).

The constant temperature at the surface represents the 1st kind boundary condition. It approaches the process of wood pressing, when press hot metal tables as heat reservoir touch the wood surfaces [7]. Then the variable temperature at the surface can be modelled according the Duhamel theorem. If wood is heated by external radiant source, linear increase surface temperature in time of heating will describe the situation [8].

The constant heat flux at the surface represents the 2nd kind boundary condition. It approaches the wood heating, when metal table touching the wood surface is heated by electric current [9]. Also zero heat flux represents the adiabatic process or symmetry in temperature field.

The constant proportionality between heat flux at the surface and the surface temperature represents the 3rd kind boundary condition. It describes the surface phenomena during heat transfer when fluid touches the wood surface. Also, heat transfer between low temperature radiant sources and wood specimen fulfil this condition [5]. Then heat transfer coefficient is proportional to emissivity of wood.

The coupling of the first and second boundary conditions enables to exclude the time from boundary condition. Such situation occurs at the wood surface touching the solid [10].

The application of similar planar heat source as used by [9] in their unsteady state method and apparatus arrangement of method as used by [11] continues to method used in the Department of Wood Science at Technical University in Zvolen. The sample arrangement of the method, named as quasistationary method [2], is depicted at **Figure 1**.

The eight specimens' arrangement is symmetric which fulfil the following boundary conditions:

$$\frac{\partial T}{\partial x}\bigg|_{x=d_R} = \frac{q}{\lambda} \tag{14}$$

$$\frac{\partial T}{\partial x}\bigg|_{x=0} = 0 \tag{15}$$

$$T(x,0) - T_0 = 0 \tag{16}$$

where d_R is thickness of one specimen. Eq. (14) represents the constant flux at the surface $x = d_R$. The very thin (0.01 mm) NiCr foil is heated by direct electric current. It is produced
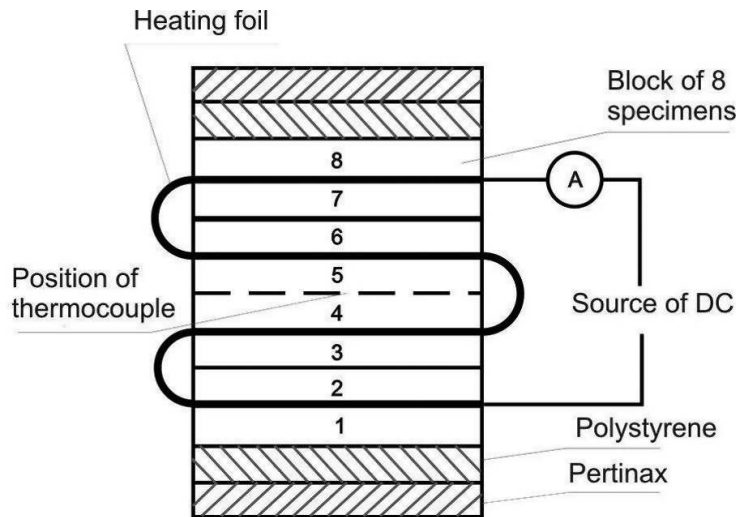
Figure 1. The diagram of quasistationary method.

by stable laboratory DC source. It is assumed the heat is symmetrically distributed to adjacent specimens, therefore, heat flux q is computed:

$$q = \frac{1}{2}\frac{RI^2}{S} \tag{17}$$

where R is resistance, I is direct current, S is rectangular area of one foil surface touching the specimen. Eq. (15) describes zero flux at the centre of the block of the eight specimens. The initial condition (16) prescribes constant temperature T_0 throughout the specimen at the beginning of experiment. Then, the solution of heat conduction equation in one dimension has the form:

$$T(x,t){-}T_0 = \frac{qd_R}{\lambda}\left[\frac{\alpha t}{d_R^2} - \frac{d_R^2{-}3x^2}{6d_R^2} + \sum_{n=1}^{\infty}(-1)^{n+1}\frac{2}{(n\pi)^2}\cos\left(n\pi\frac{x}{d_R}\right)e^{-(n\pi)^2\frac{\alpha t}{d_R^2}}\right] \tag{18}$$

The sum in Eq. (18) can be significantly active only at the beginning of the experiment. It is possible to neglect it for sufficient long time. And finally, the linear increase of temperature in the middle of the 8 block of specimens is:

$$T(0,t){-}T_0 = \frac{qd_R}{\lambda}\left(\frac{\alpha t}{d_R^2} - \frac{1}{6}\right) = At + B = \frac{q}{\rho d_R}\frac{1}{c}t - \frac{qd_R}{6}\frac{1}{\lambda} \tag{19}$$

If A is the slope and B is the intercept of such linear increase of temperature in time, the formulas are valid for thermal properties:

$$c = \frac{q}{Ad_R\rho} \tag{20}$$

$$\lambda = -\frac{qd_R}{6B} \tag{21}$$

$$\alpha = -\frac{d_R^2 A}{6B} \tag{22}$$

The method is named as quasistationary method because characteristic linear temperature increase in time is present. Thermal diffusivity can be determined, even the flux from source is not known. Moreover, if density is known, the specific heat is determined. The characteristic temperature increase in time for whole duration of experiment is in **Figure 2**.

The one dimensional adiabatic model (18) is proper for thin radial boards, thin specimen with the thickness in longitudinal direction or very distant tangential boards from the pith. Wood is treated as linear orthotropic material. The solution:

$$T(r,\varphi,t) - T_0 = \frac{qr\varphi_{max}}{\lambda_T}\left[\frac{\alpha_T t}{(r\varphi_{max})^2} - \frac{\varphi_{max}^2 - 3\varphi^2}{6\varphi_{max}^2} + \sum_{n=1}^{\infty}(-1)^{n+1}\frac{2}{(n\pi)^2}\cos\left(n\pi\frac{\varphi}{\varphi_{max}}\right)e^{-(n\pi)^2\frac{\alpha_T t}{(r\varphi_{max})^2}}\right] \tag{23}$$

where r ≠ 0 m, is suitable for the block of 8 wooden wedges and wood is treated as cylindrical orthotropic material. The angle between the marginal radial surfaces of one wedge is φ_{max}. Then computing of thermal properties from temperature increase in time is the similar to previous formulas (20)–(22).

Models (18) and (23) are adiabatic, there is no lateral transfer of heat to surrounding there and, therefore, the models are one-dimensional. The three dimensional model enables to simultaneously predict all material thermal diffusivity eigenvalues in principal anatomical directions together with its specific heat. Such model should describe also lateral heat transfer to
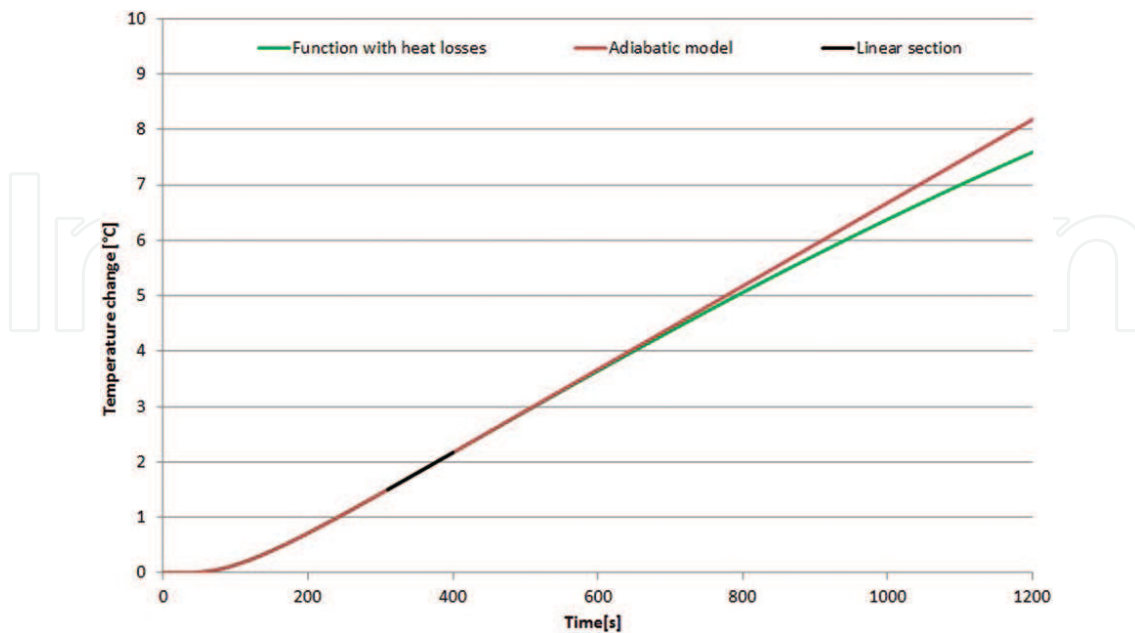

Figure 2. The adiabatic solution (18) together with the linear part t ε (300; 400)s typical for quasistationary method (α= 1.5 × 10^{-7} m^2 s^{-1}, c = 1.8 kJ kg^{-1} K^{-1}, ρ = 416 kg m^{-3}).

surrounding. Adiabatic model (18) is extended to three dimensions with heat transfer from lateral surfaces [12–14]:

$$
T(x, y, z, t) - T_0 = \frac{8q}{c\rho d_L} \sum_{r=1}^{\infty} \sum_{p=1}^{\infty} \sum_{m=1}^{\infty} \frac{(\sin\mu_r)\left(\cos\frac{\mu_r}{d_T}z\right)}{(\mu_r + (\sin\mu_r)(\cos\mu_r))} \frac{(\sin\mu_p)\left(\cos\frac{\mu_p}{d_R}y\right)}{(\mu_p + (\sin\mu_p)(\cos\mu_p))}
$$

$$
\frac{\mu_m\left(\cos\frac{\mu_m}{d_L}x\right)}{(\mu_m + (\sin\mu_m)(\cos\mu_m))} \left(\frac{1 - e^{-\left(\mu_m^2\frac{\alpha_L}{d_L^2} + \mu_p^2\frac{\alpha_R}{d_R^2} + \mu_r^2\frac{\alpha_T}{d_T^2}\right)t}}{\mu_m^2\frac{\alpha_L}{d_L^2} + \mu_p^2\frac{\alpha_R}{d_R^2} + \mu_r^2\frac{\alpha_T}{d_T^2}} \right)
\tag{24}
$$

where d_L, d_R, d_T are half of dimensions and α_R, α_T, α_L are thermal diffusivities in longitudinal, radial and tangential directions, c is specific heat capacity and ϱ is density at given moisture content. Eq. (24) is the solution of heat conduction Eq. (13), when the block of specimens is in environment of air. The extension for convection at boundaries is accompanied with heat transfer coefficients h and Biot numbers Bi at boundaries. Such extension significantly reduces the number of specimens in quasistationary method to number of 2. Characteristic equations are (for the anatomical direction):

$$
\mu_m tg\mu_m = \frac{h_L d_L}{\lambda_L} = Bi_L \tag{25}
$$

$$
\mu_p tg\mu_p = \frac{h_R d_R}{\lambda_R} = Bi_R \tag{26}
$$

$$
\mu_r tg\mu_r = \frac{h_T d_T}{\lambda_T} = Bi_T \tag{27}
$$

with constant initial temperature through the specimen T_0. The solution (24) fulfils the next boundary conditions:

$$
-\lambda_L \frac{\partial T}{\partial x}\bigg|_{x=d_L} = h_L(T|_{x=d_L} - T_0) \tag{28}
$$

$$
-\lambda_R \frac{\partial T}{\partial x}\bigg|_{y=d_R} = h_R(T|_{y=d_R} - T_0) \tag{29}
$$

$$
-\lambda_T \frac{\partial T}{\partial x}\bigg|_{z=d_T} = h_T(T|_{z=d_T} - T_0) \tag{30}
$$

$$
\frac{\partial T}{\partial x}\bigg|_{x=0} = -\frac{\varphi}{\lambda_L} \tag{31}
$$

$$
\frac{\partial T}{\partial y}\bigg|_{y=0} = 0 \tag{32}
$$

$$
\frac{\partial T}{\partial z}\bigg|_{z=0} = 0 \tag{33}
$$

where Bi_L, Bi_R, Bi_T are Biot numbers at principal anatomical sections.

The information from only one thermocouple, which is placed in the middle of specimens block, is able to be fully utilized only if material is isotropic in plane of source. Otherwise, more thermocouples must be used to determine all wood thermal properties simultaneously. Another possibility is to rotate the samples considering the position of source and principal anatomical directions. Later all three sets of data will be processed simultaneously. The model (24) is nonlinear. The starting values for least square method are found after utilization of adiabatic models (18) and (23). The solution of heat conduction equation is the base of inverse problem. The solution T_{teor} is compared to measured temperature values at given time T_{exp} in least square criterion Q:

$$Q(c, \alpha_L, \alpha_R, \alpha_T, Bi_L, Bi_R, Bi_T) = \sum_{i=1}^{N} \left(T_{iteor}(c, \alpha_L, \alpha_R, \alpha_T, Bi_L, Bi_R, Bi_T, t_i) - T_{iexp}(t_i) \right)^2 \qquad (34)$$

where N is number of measurement.

The results from quasistationary method in three dimensions are summarized in **Tables 1** and **2**.

The beech (*Fagus sylvatica*, L.) and fir (*Abies alba*, Mill.) wood were tested for thermal properties as they are widely used in furniture and construction industry. The 18 beech cubic samples of edge dimension 100 mm in principal anatomical directions were cut from outer part of stem with diameter of 35 cm to be linear orthogonal as much as possible. The specimens' equilibrium moisture content was 12%, and their surfaces were sanded to cube shape of measured dimensions. The 1-cm thick specimen was cut from cubes to place the thermocouple 1 cm far from heating foil. The measurement was performed in climatic chamber with air relative humidity of 65% and temperature of 20°C. The specimens were fixed in the beech rack around the heating foil. The temperature 20°C was initial one and applied heating flux was 145 W m^{-2}. Then temperature was recorded every 5 s. Later on the data in file of recorded times and temperatures were sorted, because long time of results computation according to Eqs. (24) and (34). The experiment was performed three times, each time the heating foil touched the

d_L [m]	0.1082
α_L [m^2 s^{-1}]	2.9×10^{-7}
α_R [m^2 s^{-1}]	1.7×10^{-7}
α_T [m^2 s^{-1}]	1.2×10^{-7}
c [J kg^{-1} K^{-1}]	1900
λ_L [W m^{-1} K^{-1}]	0.38
λ_R [W m^{-1} K^{-1}]	0.23
λ_T [W m^{-1} K^{-1}]	0.16
ρ [kg m^{-3}]	703.9

Table 1. Average thermal properties of beech wood [13].

d_L [m]	0.0542
α_L [m^2 s^{-1}]	5.2×10^{-7}
α_R [m^2 s^{-1}]	2.4×10^{-7}
α_T [m^2 s^{-1}]	1.8×10^{-7}
c [J kg^{-1} K^{-1}]	1700
λ_L [W m^{-1} K^{-1}]	0.36
λ_R [W m^{-1} K^{-1}]	0.17
λ_T [W m^{-1} K^{-1}]	0.13
ρ [kg m^{-3}]	414.5

Table 2. Average thermal properties of fir wood [14].

different section. The results are embedded in **Table 1** and the evaluated temperatures along with computed results are depicted in **Figure 3**.

The same experiment was performed with 10 fir samples. The additional differences were in dimensions (the fir cube edge was 50 mm), position of thermocouple was 3.4 mm next to heating foil and heating flux was 100 W m^{-2}. The results for fir wood samples are in **Table 2** and depicted in **Figure 4**. The convection at boundary was free during both experiments (heat transfer coefficient h_L = 8.9 W m^{-2} K^{-1} at beech cross section and heat transfer coefficient 1.0×10^1 W m^{-2} K^{-1} at fir anatomical sections).

The thermal properties have advantage in common definitions. The solutions of heat conduction equation are expressed in dimensional criterion or numbers. They describe the conduction
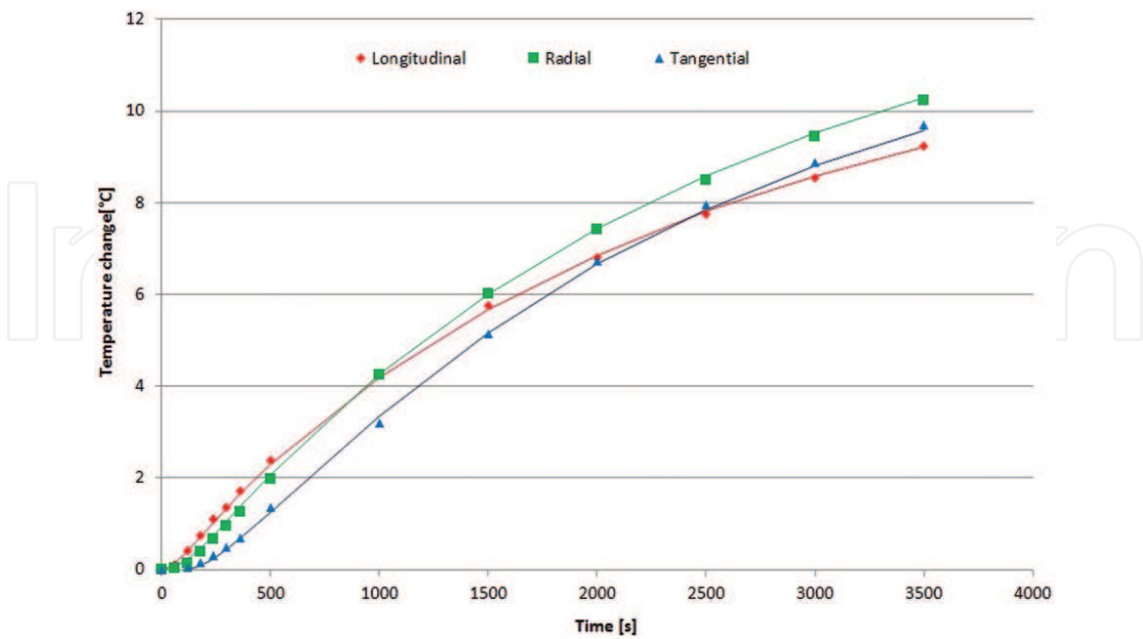

Figure 3. Temperature increase in point [1; 0; 0]cm measured from heating foil placed in different anatomical sections of beech wood. Sum of squares for 42 temperature measurements was 0.21 K^2 [13].
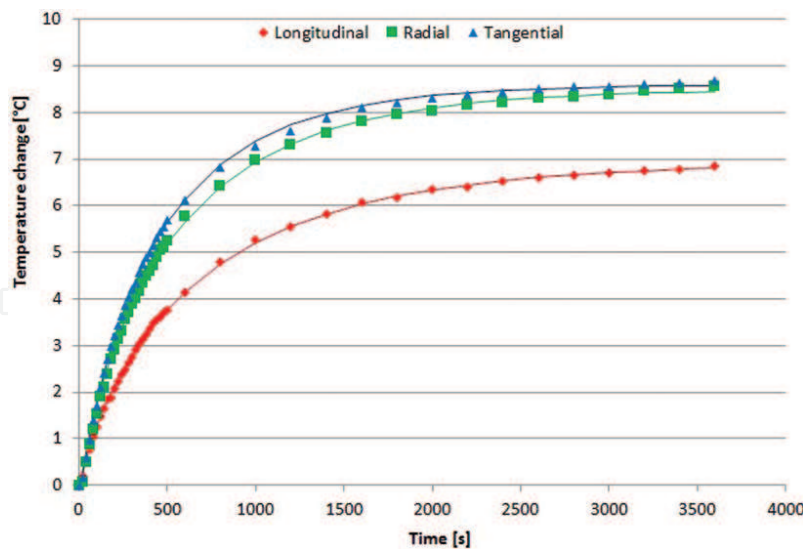
Figure 4. Temperature increase in point [0.34; 0; 0]cm measured from heating foil placed in different anatomical sections of beech wood. Sum of squares for 126 temperature measurements was $0.50K^2$ [14].

in similar objects and, moreover, the results can be extended to non-homogeneous objects. Typical example is summing the thermal conductivities in building physics. The result depends on arranging the layers and heat flux direction, **Figure 5**.

Both formulas in **Figure 5** are valid in composite wall at steady state. The following formulas enable the infinitesimal extension to non-homogeneous continuum [7]:

$$\lambda_\perp = \frac{d}{\int_0^d \frac{dx}{\lambda(x)}} \tag{35}$$

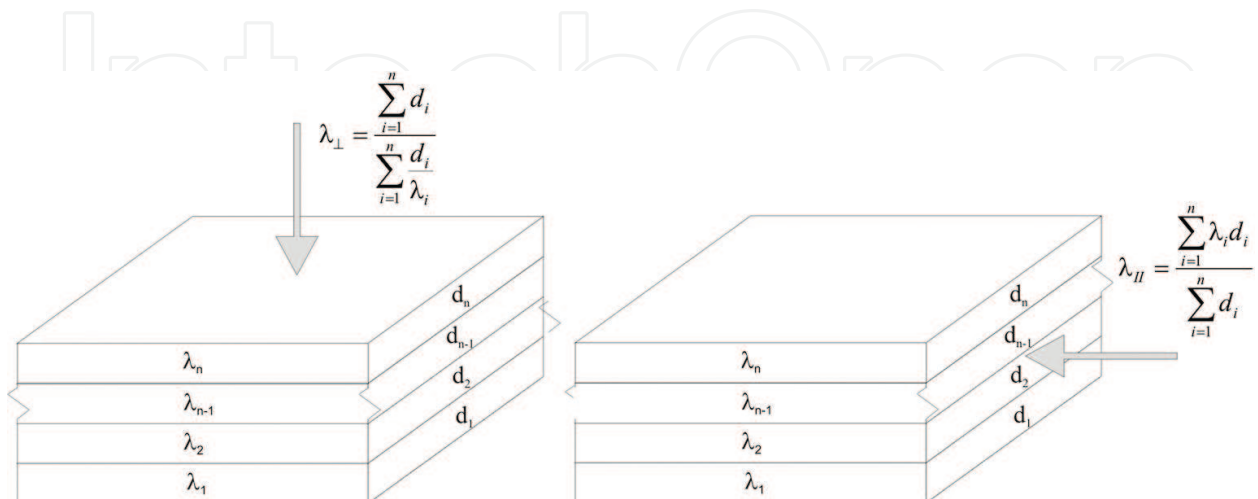$$\lambda_{II} = \frac{1}{d}\int_0^d \lambda(x)dx \tag{36}$$

Figure 5. The basic pattern of layers and heat flux (arrow) in composite wall during conduction.

The steady state solution (37) in log with infinite length (for example as element of log cabin houses as is described in Ref. [15], **Figure 6**) is utilized for computing heat flux $\mathbf{q} = q\mathbf{i}$ (38) passing through it:

$$T - T_0 = \frac{1}{2}(T_2 - T_0)\left(1 - \left(\frac{r}{R}\right)^{\sqrt{\frac{\alpha_T}{\alpha_R}}}\cos(\varphi)\right) \tag{37}$$

$$q = \sqrt{\lambda_R \lambda_T}\,\frac{T_2 - T_0}{2R} \tag{38}$$

The "enlarge cracks" are not necessary present in log after conditioning, but regularly one occur after kerfing of logs from sap to pith because shrinkage differences in various anatomical directions.

One of the haptic phenomena—tactile warm—is related to thermal properties [16]. Touching wood at cold winter or hot summer is more pleasant than touching many other materials. One of the possible reason and next explanation of tactile warms as physiological event inheres in value of formed temperature at the surface between wood and human (living) body [17]. The formed temperature is closer to temperature of human body before touching wood either in cold winter or hot summer. The quantity responsible to this event is called thermal effusivity e:

$$e = \sqrt{\lambda c \rho} \tag{39}$$

as a square root of product of thermal conductivity, specific heat and density. Let two semi-infinite solids have different initial temperatures, T_{01}, T_{02} and no additional sources or sinks act at the surface or in their volumes. Steady temperature T_S at the surface between these two semi-infinite solids in contact is influenced by their effusivities e_1, e_2:

$$T_s = T_{02} + (T_{01} - T_{02})\frac{e_1}{e_1 + e_2} = T_{01} + (T_{02} - T_{01})\frac{e_2}{e_1 + e_2}. \tag{40}$$

The effusivity values for previously mentioned beech and fir wood are in **Table 3**.
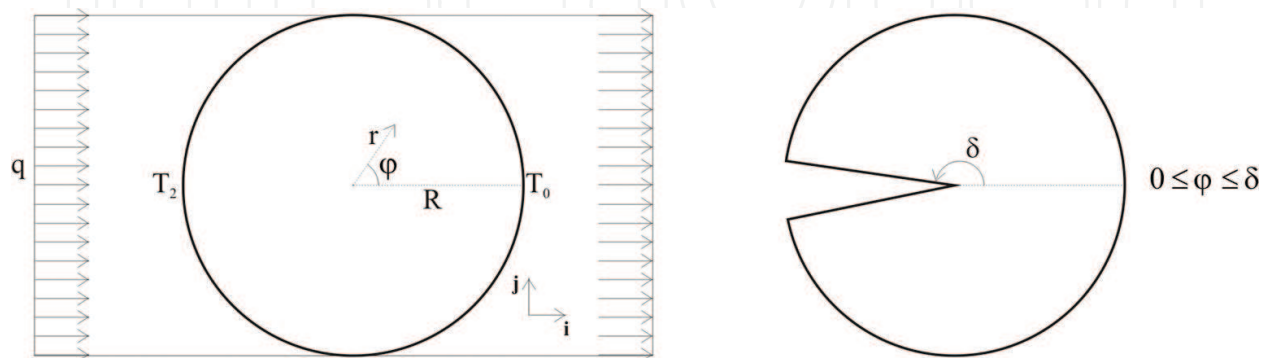

Figure 6. Orientation of heat flux through log (cross section at left side); orientation of heat flux and position of crack due to anisotropy of shrinkage (cross section at right side).

Material	Direction		
	e_L [W m^{-2} K^{-1} s$^{0.5}$]	e_R [W m^{-2} K^{-1} s$^{0.5}$]	e_T [W m^{-2} K^{-1} s$^{0.5}$]
Beech	7.1×10^2	5.5×10^2	4.6×10^2
Fir	5.0×10^2	3.5×10^2	3.0×10^2

Table 3. Thermal effusivity of beech and fir wood in principal anatomical directions.

The largest thermal effusivity eigenvalue is in wood longitudinal direction. It results to the larger drop value of human skin temperature or smaller drop value of wood surface temperature. The opposite is valid for wood tangential direction.

3. Factors related to thermal properties

The most of the factors are quantities: density, moisture content and temperature which are scalars. The dependency on anatomical direction—the direction of measurement, is crucial for distinguishing the thermal property as scalar or tensor.

3.1. Anatomical direction

Specific heat is a scalar quantity neither it is mass nor volume specific heat capacity, they do not depend on anatomical direction. Thermal conductivity and thermal diffusivity are second order tensors. Their eigendirections coincide with principal anatomical directions as a result of measurement (also proved by Sonderegger et al. [18], Vay et al. [19]). Also their eigenvalues determine the dimensions [2.d_{Rmin}, 2.d_{Tmin}, 2.d_{Lmin}] of the parallelepiped of the slowest average temperature change in its volume V:

$$d^3_{Rmin} = \frac{V}{8} \frac{\alpha_R}{\sqrt{\alpha_T \alpha_L}}, \quad d^3_{Tmin} = \frac{V}{8} \frac{\alpha_T}{\sqrt{\alpha_L \alpha_R}}, \quad d^3_{Lmin} = \frac{V}{8} \frac{\alpha_L}{\sqrt{\alpha_R \alpha_T}} \tag{41}$$

Then, the ratio of optimal dimensions for beech in longitudinal, radial and tangential directions is:

1.6:1.2:1

and for fir:

1.7:1.2:1.

The characteristic feature of the optimal parallelepiped is the smallest transferred heat through its surfaces, for example, from its volume.

3.2. Density

Wood is regarded as non-homogeneous material. This conclusion is strongly supported by microscopy [20]. Therefore, for every homogeneous part of wood volume, we should prescribe

the equations with appropriate boundary conditions. The phenomenon of continuum for whole wood volume has been more efficient yet. We often neglect mass of air inside wood as it is measured in air environment. The air volume in wood is not neglected. Therefore, mass specific heat capacity c_0 does not depend on oven dry density or anatomical species. Many experiments proved the significant thermal conductivity dependency on oven dry density. Wood contains air as a good thermal insulator, therefore, a smaller value of oven dry density results in a smaller value of wood thermal conductivity. Perhaps one of the first relationships was set in theory of thermal bridges by Kollmann and Malmquist [21]. The theory utilizes the equations in **Figure 5**, and oven dry wood is treated as composites of substance and air. Also, the theory stated the dependency of thermal conductivity on anatomical directions according to value of bridge factor. In spite of thermal bridge theory indisputability, it seems to be more efficient the relationship between thermal conductivity and density at given moisture content. If density is zero then no matter exists for conduction and the simplest non-homogeneous model (layer of wood substance next to layer of air) predicts linear relationship between thermal conductivity and density at given moisture content and later no influence of density at given moisture content on thermal diffusivity. These results are in contrary to results in **Tables 1** and **2**, so the simplest non-homogeneous model does not hold for wood well. Week relationship between thermal diffusivity and density at given moisture content was published by Harada et al. [22].

3.3. Moisture content

The ratio of water mass specific heat to air mass specific heat is more than one. It follows from mixing rule [23]:

$$c = \frac{c_0 + w c_{H_2O}}{1 + w} - \frac{1}{1 + w} \frac{d(Q_{z0} - Q_z)}{M_{H_2O} dT}$$

(42)

where Q_z, resp. Q_{z0} is wetting heat at given moisture content, resp. in oven dry state and is represented in J mol^{-1}. The last expression of Eq. (42) is zero for free water. The water molecules in wood behave as sinks during evaporation. It should be noted, that diffusion of water in wood is approximately 100 times slower than conduction of heat through wood at room temperatures and these two processes can be studied separately [7]. The relationship between equilibrium moisture content and species is weak. Also, the influences of moisture content and oven dry density on thermal conductivity and thermal diffusivity are studied separately. The density at given moisture content is directly connected with thermal diffusivity computing formula. Then, the influence of moisture content on thermal diffusivity is set into density at given moisture content.

3.4. Temperature

The linear function of mass specific heat capacity at zero moisture content on temperature was provided by Perelygin [24] (according to Požgaj et al. [7]):

$$c_0 = 1.571 + 0.00277 \vartheta \ [\text{kJkg}^{-1}\text{K}^{-1}]$$

(43)

and [25] (according to Radmanović et al. [26]):

$$c_0 = 1.1136 + 0.004856 \vartheta \ [\text{kJkg}^{-1}\text{K}^{-1}] \tag{44}$$

and others in the range ϑ = 0–100°C, even [27] published theoretical function determined from Debye's theory for solid substances at constant volume. The advantage of linear relationship is in easy computation of average specific heat value. Also, determination of adiabatic temperature leads to quadratic equation. The influence of temperature on thermal conductivity is studied by setting initial temperatures to different levels and only small temperature drop between surroundings and tested specimen causes heat transfer. Then results are tested by regression even the results were obtained with method using the heat conduction equation solution with constant coefficients. Later, on such results are used in numerical inverse or direct problem solutions as starting values. The solving of nonlinear equation is better solution to incorporate the dependence of thermal properties on temperature. One of the possibilities to overcome this problem is designing the dependency of thermal conductivity on temperature, for example as polynomial:

$$\lambda = k(T - T_\infty)^n \tag{45}$$

where T_∞, k, n are constants and heat conduction equation is rearranged to the parabolic equation again:

$$\frac{\partial F}{\partial t} = \alpha \frac{\partial^2 F}{\partial x^2} \tag{46}$$

where

$$F = \frac{k(T - T_\infty)^{n+1}}{n+1} \tag{47}$$

Also, the Arhenius dependence of thermal conductivity on temperature leads to Eq. (46), but transformation from F to T is nonlinear and must be find numerically. The numerical solutions of nonlinear heat conduction equation were showed by Zhao et al. [28]. Their procedure was applied on experimental data of varying temperature and moisture content according to industrial practise.

3.5. Thermal expansion

The change of heat capacity at constant pressure C_P and at constant volume C_V is distinct for gases. This phenomenon is often neglected for wood even the coefficient of volume thermal expansion α_e is determined:

$$V - V_0 = \gamma_e V_0 \vartheta \tag{48}$$

where V is volume at temperature ϑ in °C, V_0 is the volume at 0°C. Then, difference in capacities is:

$$C_P - C_V = TV \frac{\gamma^2}{K_T} \tag{49}$$

where T is temperature in K and K_T is isothermal compressibility. The coefficient of linear thermal expansion α_e is defined:

Material	Property			
	$10^6 \times \alpha_{eT}$ [°C^{-1}]	$10^6 \times \alpha_{eR}$ [°C^{-1}]	$10^6 \times \alpha_{eL}$ [°C^{-1}]	$10^6 \times \gamma_e$ [°C^{-1}]
Fir[a]	31.6	21.7	3.90	57.2
Beech[b]	40.3	31.8	3.1–4.5	75.2–76.6

Table 4. The coefficient of linear thermal expansion of fir and beech wood at zero moisture content ([29][a], [30][b]) and coefficient of volume thermal expansion.

$$d - d_0 = \alpha_e d_0 \vartheta \tag{50}$$

where d is dimension at temperature ϑ in °C, d_0 is the dimension at 0°C. The relationship between coefficients of linear and volume thermal expansion is:

$$\gamma = \alpha_{eL} + \alpha_{eR} + \alpha_{eT} + \alpha_{eL}\alpha_{eR} + \alpha_{eR}\alpha_{eT} + \alpha_{eL}\alpha_{eR} + \alpha_{eL}\alpha_{eR}\alpha_{eT} \approx \alpha_{eL} + \alpha_{eR} + \alpha_{eT} \tag{51}$$

where L, R, and T denotes principal anatomical directions (**Table 4**).

The dimension of wood equilibrates as fast as temperature of wood equilibrates. And thermal diffusivity is also property characterizing how fast the dimensions of wood equilibrate during equilibrating its two different temperatures. Let it say, for temperature T in point x_0 and time t is valid:

$$T(x_0, t) = T_\infty + (T_0 - T_\infty)e^{-\frac{h}{d_0}t} \tag{52}$$

with no-zero flux at the surface $x_0 = d_0$, where T_∞ is equilibrium temperature and T_0 is initial temperature. If conduction occurs during constant pressure, the new position of point x_0 will be coordinate x:

$$x = x_0 \left(1 + \alpha_e(T_0 - T_\infty)e^{-\frac{h}{d_0}t}\right) \tag{53}$$

Two dimensional problems are more complicated, but bonded oven dry specimens with thin thicknesses oriented in different anatomical directions and different initial temperatures show distinct deflections due to anisotropy of coefficient of linear thermal expansion in equilibrium.

4. Conclusion

The answers to the three questions mentioned in Section 1 are closely related to thermal properties. Wood as natural material is characterized by its properties, which definitions are precisely stated. The definitions are often expressed as equations which solutions are used in measuring methods. Because of many measuring methods of wood thermal properties and large variability of their results, methods must be clearly explained and their technical representation must be closed as much as possible to assumptions used in solutions. The

large variability of the results is connected not even with inherent categorization of wood species, but for example also position in steam causes variability of the results. There are several factors which affect the wood thermal properties in wood and a lot of others waited for discovering [31]. The management of the industrial processes in real time according to properties are really difficult. The designs of the heat transfer processes are connected to wood thermal properties. After measuring of the results, they are used in solutions of different similar direct problems, for example in furniture design or building physics and others.

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