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Thermal conductivity of Norway spruce and European beech in the anatomical directions[1)]

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Abstract: *Thermal conductivity of Norway spruce and European beech in the anatomical directions.* Thermal conductivity, thermal diffusivity and heat capacity of Norway spruce (*Picea abies* [L.] Karst.) and European beech (*Fagus sylvatica* L.) were determined for all principal directions (radial, tangential and longitudinal) depending on the moisture content (MC). Further, between the three principal directions, the thermal conductivity was determined in 15° steps.
The results show that thermal conductivity increases with increasing MC and shows the highest increase in the tangential and the lowest in the longitudinal direction. Thermal conductivity is higher for beech than for spruce in all anatomical directions and the conductivity for both species is more than twice as high in the longitudinal direction than perpendicular to the grain. The highest thermal conductivity is found for beech at a grain angle of about 15°. The lowest thermal conductivity shows spruce at an angle of about 60° between the tangential and the radial direction.

Keywords: thermal conductivity, grain orientation, moisture content, beech, spruce

INTRODUCTION

Accurate knowledge of thermal properties of wood are of high interest in the wood industry such as drying, thermal treatment, steaming and hot gluing to optimize their process technology, and are more and more essential in building physics for modelling energy-efficient timber constructions. Thereby, thermal conductivity, heat capacity and thermal diffusivity are the most important parameters necessary to most accurately calculate and simulate the thermal behaviour of wood. Since wood is an anisotropic material, thermal conductivity and diffusivity depend strongly on the anatomical direction. Both parameters are about 3 to 20% higher in the radial than in the tangential direction and in the longitudinal direction by about 1.5 to 2.75 times higher than perpendicular to the grain. In contrast, the heat capacity is a material-immanent parameter independent from the anisotropic structure and has similar values for all wood species. All three parameters are strongly influenced by temperature and moisture (cf. Kühlmann 1962, Kollmann and Côté 1968, Steinhagen 1977).
The three parameters have the following relationship:

$$\alpha = \frac{\lambda}{c \cdot \rho} \tag{1}$$

where α is the thermal diffusivity [m²/s], λ the thermal conductivity [W/mK], c the heat capacity [J/kgK] and ρ the density [kg/m³].
The influence of temperature, moisture and density on the thermal conductivity in and perpendicular to the fibre direction is described in detail by Kollmann and Côté (1968) and is approximately linear in the density range from 200 to 800 kg/m³, in the MC range from 5 to 35% and in the temperature range from -50° to 100°C.

The goal of the presented investigation is a widespread determination of the thermal conductivity of the two commercially important wood species, Norway spruce (*Picea abies* [L.] Karst.) and European beech (*Fagus sylvatica* L.), in the anatomical directions.

MATERIAL AND METHODS

Material

For the investigations, European beech and Norway spruce samples with dimensions of about 200 mm x 200 mm x 20 mm were tested. The samples were cut from one beech and two spruce trees from the region of Zurich. The thermal conductivity was measured in the three principal anatomical directions (radial, tangential, longitudinal) and in 15° steps between these directions. Therefore, 18 variations per wood species, each of them with 4 specimens, were tested.
Before testing, the specimens were air-conditioned at 20°C and 65% relative humidity (20/65). The specimens used for the measurements in the three main directions were additionally conditioned and tested at 20/35, 20/80, 20/88 and at oven-dry conditions.

Experimental setup

The measurements of the thermal conductivity were carried out with the single-specimen guarded hot plate apparatus λ-Meter EP500 (Lambda-Messtechnik GmbH, Dresden) according to ISO 8302. Figure 1 schematically shows the construction of the apparatus.

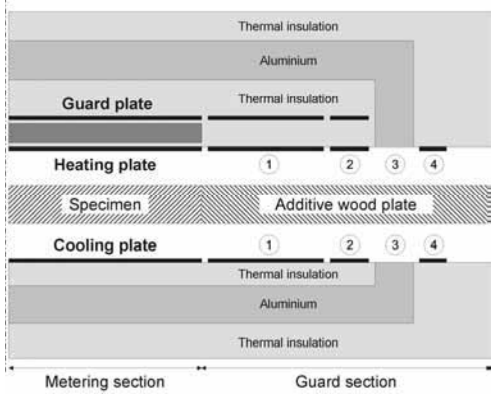

Figure 1 Simplified half-diagram of the single-specimen guarded hot plate apparatus. 1, 2, 4 are the inner, middle and external heating guard rings and 3 the cooling ring (or tempering ring) to protect the test specimen from environmental influences.

Normally, the samples have dimensions of 500 mm x 500 mm x sample thickness and the thermal conductivity would be measured circularly with a diameter of 200 mm in the middle of the sample. The outer parts serve as protection from environmental influences. Since the investigated samples had only dimensions of about 200 mm x 200 mm, they were placed centrally on the plate covering the measuring range and insulated from the environment with wood plates of similar fibre orientation and thicknesses so that the whole area of 500 mm x 500 mm was covered.
The thermal conductivities were measured at three temperatures: 10°, 20° and 30°C (for spruce between the radial and tangential direction: at 10°, 25° and 40°C). A difference of 5 and 10 K was used between the heating and the cooling plate, respectively, to measure

parallel and perpendicular to the fibre direction. From the values at the three temperatures, the thermal conductivity at 10°C was determined by a linear regression through the values. The slope of the regression then corresponds to the temperature coefficient of the thermal conductivity.

RESULTS AND DISCUSSION

The thermal conductivities of Norway spruce and European beech at 10°C in the three principal anatomical directions depending on MC are shown in Figure 2. For both wood species, the thermal conductivities in the longitudinal direction are more than twice as high as in the directions perpendicular to the grain, and clearly higher in the radial than in the tangential direction.

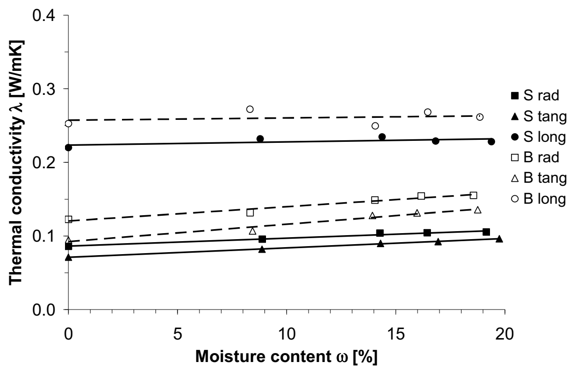

Figure 2 Thermal conductivity (λ) of Norway spruce (S) and European beech (B) in the radial (rad), tangential (tang) and longitudinal (long) directions depending on moisture content (ω). Linear regressions of Norway spruce (solid) and of European beech (dashed).

Table 1 Thermal conductivity (λ) depending on MC (ω) at different climates (in brackets, temperature/rel air humidity) determined on the regression $\lambda = A + B \cdot \omega$, where $A = \lambda_{10.dry}$ (λ at dry condition and 10°C) and $B = \Delta\lambda_{\omega}$ (change of λ per percent MC). R^2 = coefficient of determination.

Wood species	Direction	Air-dry density [kg/m^3]	ω (20/35) [%]	ω (20/65) [%]	ω (20/80) [%]	ω (20/88) [%]	A (= $\lambda_{10.dry}$) [W/mK]	B (= $\Delta\lambda_{\omega}$) [W/mK]	R^2
Norway spruce	radial	446	8.9	14.3	16.4	19.2	0.086	$1.08 \cdot 10^{-3}$	0.97
	tangential	410	8.9	14.3	16.9	19.7	0.071	$1.28 \cdot 10^{-3}$	0.999
	longitudinal	425	8.8	14.4	16.8	19.4	0.223	$0.44 \cdot 10^{-3}$	0.37
European beech	radial	640	8.3	14.0	16.2	18.6	0.120	$1.93 \cdot 10^{-3}$	0.95
	tangential	682	8.4	13.9	16.0	18.8	0.092	$2.35 \cdot 10^{-3}$	0.96
	longitudinal	674	8.3	14.1	16.5	18.9	0.257	$0.31 \cdot 10^{-3}$	0.06

For beech wood, the moisture-dependant gradients of thermal conductivity are nearly twice as high than for spruce wood in the radial and tangential directions, and are higher in the tangential than in the radial direction for both species. In contrast, the moisture-dependant gradient in the longitudinal direction is very low for both species. For elm wood (*Ulmus scabra* Mill.), Hrčka and Kurjatko (2006) also found only a small correlation between thermal conductivity and MC in the longitudinal direction. This results from a high variation of the values in this direction (cf. the low coefficient of determination (R^2) in Table 1). Otherwise, this can be attributed to the generally higher thermal conductivity of the net cell wall substance in this direction (0.65 W/mK), which is similar to the thermal conductivity of water at about 0.60 W/mK (Maku 1954 in Siau 1995). The influence of the MC would be diminished further if it were taken into account that the thermal conductivity of bound water is even lower than that of free water (McLean 1941).

Table 2 Parameters of the polynomial function $\lambda = A + B \cdot x + C \cdot x^2 + D \cdot x^3$ describing the thermal conductivity between the principal directions of spruce and beech. R^2 = coefficient of determination.

Wood species	Direction	A	B	C	D	R^2
Norway spruce	longitudinal – radial (≈ grain angle)	0.234	$-5.84 \cdot 10^{-4}$	$-3.58 \cdot 10^{-5}$	$2.88 \cdot 10^{-7}$	0.998
	longitudinal – tangential (≈ grain angle)	0.235	$1.87 \cdot 10^{-4}$	$-5.66 \cdot 10^{-5}$	$4.10 \cdot 10^{-7}$	0.999
	tangential – radial (≈ ring angle)	0.093	$1.80 \cdot 10^{-4}$	$-7.96 \cdot 10^{-6}$	$7.99 \cdot 10^{-8}$	0.75
European beech	longitudinal – radial (≈ grain angle)	0.251	$1.18 \cdot 10^{-3}$	$-6.15 \cdot 10^{-5}$	$4.06 \cdot 10^{-7}$	0.99
	longitudinal – tangential (≈ grain angle)	0.250	$1.50 \cdot 10^{-3}$	$-7.51 \cdot 10^{-5}$	$4.78 \cdot 10^{-7}$	0.99
	tangential – radial (≈ ring angle)	0.127	$4.41 \cdot 10^{-5}$	$1.15 \cdot 10^{-5}$	$-9.59 \cdot 10^{-8}$	0.95

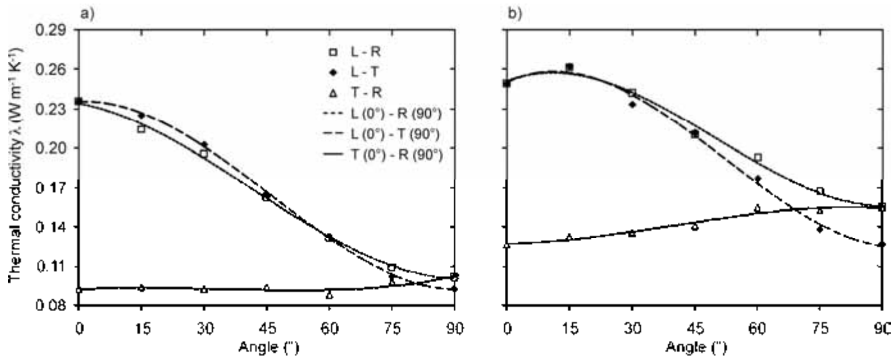

Figure 3 Thermal conductivity (λ) at 10°C in and between the principal anatomical directions of Norway spruce (a) and European beech (b) previously conditioned at 20°C and 65% RH. R = radial, T = tangential, L = longitudinal, points = measured data, lines = calculated values.

The mean temperature coefficient of the thermal conductivity perpendicular to the fibre results in 0.22 % per K for spruce and 0.25 % per K for beech and both are in good agreement with values by Kühlmann (1962), Steinhagen (1977) and Suleiman et al. (1999). The temperature coefficient parallel to the fibre (0.39 % per K) is clearly higher for both species than it is perpendicular to the fibre. This is in contrast to the measurements of Suleiman et al. (1999), who measured lower temperature coefficients parallel to the fibre rather than perpendicular. The differences may be influenced by the different temperature ranges and measuring methods and should be further investigated.

Figure 3 shows the run of the curves of the thermal conductivity between the three principal anatomical directions for Norway spruce and European beech. To increase comparability, the thermal conductivities determined at 10°C after reaching equilibrium MC at standard climatic conditions of 20°C and 65% relative humidity (RH) were therefore corrected to a uniform density of 427 kg/m^3 for spruce and 673 kg/m^3 for beech wood using the following equation:

$$\lambda_{cor} = \lambda_{meas} + \left(\frac{\lambda_{meas} - \lambda_{air}}{\rho_{meas}}\right)(\rho_{cor} - \rho_{meas}) \qquad (2)$$

where λ_{cor} is the thermal conductivity corrected to a uniform density, λ_{meas} the measured thermal conductivity of the sample, λ_{air} the thermal conductivity of the air (= 0.026 W/mK), ρ_{cor} the uniform density and ρ_{meas} the measured density of the sample.

The gradient between two main directions was then determined as a polynomial function of third degree. The parameters are presented in Table 2. Perpendicular to the grain, the thermal conductivity of beech increases slightly with increasing ring angle (angle between the tangential and the radial direction) whereas the thermal conductivity of spruce has the lowest value on a ring angle of 60°. This may be due to the different anatomical composition of the two species. Whereas the density within an annual ring of beech only slightly varies, the densities of early wood and late wood of spruce differ by a factor three so that it can be compared with a layered material. Thus, without the influence of the rays, the thermal conductivity in the radial direction would be clearly lower than in the tangential direction (analogous to series connections compared with parallel connections). This means for a ring angle of 60°, although the influence of the rays has already decreased, there is still considerable influence of the earlywood and latewood layers, which reduces the thermal conductivity. Moreover, as a result of the misalignment of the cells in the tangential direction, the longest way along the cell walls – at least in the early wood – could be stated for spruce at a ring angle of about 60°.

From the directions perpendicular to the grain – radial and tangential – to the longitudinal direction, the highest gradient of thermal conductivity was found between a grain angle of 15° and 75° for both species. Whereas the highest thermal conductivity for spruce was measured in the longitudinal direction, for beech it was found at a grain angle of 15°. This is assumed to be influenced by a high microfibril angle (MFA) in the S2 layers of the cell walls, which is stated for beech from the literature. For instance, Bucur (1986) measured a mean MFA of 18° in normal beech wood and Lehringer et al. (2009) even an MFA between 32° and 39.8° for tension and opposite wood. In contrast, Keunecke and Niemz (2008) and Keunecke et al. (2009) measured a mean MFA of about 10° for spruce wood although it varies - distributed over the whole stem - over a wide range (cf. Brändström 2001).

CONCLUSIONS

The thermal conductivity was investigated in and between the three principal anatomical directions of Norway spruce (*Picea abies* [L.] Karst.) and European beech (*Fagus sylvatica* L.). Whereas the highest thermal conductivity was determined to be in the longitudinal direction for spruce, beech had the highest thermal conductivity at a grain angle of about 15°. This may be deduced from the different microfibril angles. Also, while the lowest thermal conductivity was determined for beech in the tangential direction, the lowest thermal conductivity for spruce was found at a ring angle of about 60°. This may be due to the different portions of wood rays and the arrangement of the cells. The influence of the MC on the thermal conductivity is higher in the tangential than in the radial direction and very low in fibre direction.

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Streszczenie: *Przewodnictwo cieplne drewna świerka norweskiego i buka europejskiego w różnych kierunkach anatomicznych*. Sprawdzono przewodność, dyfuzyjność oraz pojemność cieplną drewna świerka (*Picea abies* [L.] Karst.) oraz buka (*Fagus sylvatica* L.) w głównych kierunkach anatomicznych (wzdłużnym, stycznym i promieniowym) w zależności od wilgotności materiału. Przewodność cieplna pomiędzy głównymi kierunkami anatomicznymi została zbadana w odstępach 15° . Badania wykazały że przewodność cieplna wzrasta wraz ze wzrostem wilgotności i wykazuje największy wzrost w kierunku stycznym a najmniejszy we wzdłużnym. Przewodność cieplna dla drewna buka jest wyższa niż dla świerka dla wszystkich kierunków anatomicznych, oraz w każdym z gatunków ponad dwukrotnie wyższa w kierunku zgodnym z przebiegiem włókien niż prostopadle do nich. Najwyższa przewodność cieplną charakteryzuje się drewno buka pod kątem około 15°, zaś najniższą świerka pod kątem 60° pomiędzy kierunkami stycznym i promieniowym.

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