THERMAL CONDUCTION BEHAVIOR OF WOOD AT MACROSCOPIC AND ON CELL WALL LEVEL

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The anisotropic thermal conduction behavior of wood can be expressed by the following structure of the thermal conductivity tensor \( K \):

\[
K = \begin{bmatrix}
\lambda_L & 0 & 0 \\
0 & \lambda_R & 0 \\
0 & 0 & \lambda_T
\end{bmatrix}
\]

Assumption: reference axis coincide with the principal material axis.

Off-axis thermal conductivities can be implemented by the respective rotation of the conductivity tensor \( K \).

In total, three analytical relations describe the thermal conductivity of wood between the principal anatomical directions depending on the rotation angle.

Rotation of the tensor \( K \) in the \( x_1-x_2 \) plane, about the \( x_3 \) axis, by an angle \( \alpha \) from the \( x_1 \) towards the \( x_2 \) axis yields a transformed thermal conductivity

\[
\lambda(\alpha) = \lambda_L \cdot \cos^2 \alpha + \lambda_R \cdot \sin^2 \alpha
\]

Note: Such a transformation behavior is underlying the definition of an orthotropic material behavior.
Material & Methods

- European beech and Norway spruce.

Macroscopic experiment

- Specimens with the grain at angles $\alpha$ of 0, 22.5, 45, 67.5 and 90 degrees, respectively, to the direction of heat flow, the angles referring to rotation in the longitudinal-radial plane.

Test tool: Single specimen guarded hot plate apparatus (ISO 8302).

Imaging conductivity at cell wall level

- Scanning thermal microscopy: standard AFM probe is substituted with an electrically heated one. The probe replaces one of the resistors in a Wheatstone bridge.

- Thermal changes in the probe are monitored via a feedback mechanism while at the same time topographical data are collected.

- To act as a resistive heater, a relatively high voltage is applied, which elevates the tip temperature well above the sample temperature.

- Probe temperature diminishes as a function of the thermal conductivity of the sample. Via the feedback mechanism, the probe temperature is restored to its original value while at the same time the thermal data is collected, thus providing a measure of thermal conductivity.

Vay et al. (2013) Studying thermal conductivity of wood at cell wall level by scanning thermal microscopy (SThM). Holzforschung.
Material & Methods

SThM experiment

- Samples were small cubes of beech and spruce wood with the grain at angles of 0° and 90° to the direction of heat flow.
- Smoothed with an ultramicrotome (Leica)
- Test instrument: Bruker Dimension Icon equipped with a standard SThM-probe (tip radius < 100nm)
- Surface of approximately 2x3mm²...

Cross section \(\quad\) Heat transport in parallel to the grain

Longitudinal section (Radial section) \(\quad\) Longitudinal section (Tangential section)

Heat transport transverse to the grain
Results

Guarded hot plate test

- **Data for European beech**
  - Moisture content at test ~11%
  - Density $\rho_{(\omega \sim 11\%)} = 750 \text{ kg/m}^3$
  - $\lambda_0 = 0.422 \text{ W/(m·K)}$
  - $\lambda_{90} = 0.172 \text{ W/(m·K)}$
  - $R^2 = 0.998$

- **Data for Norway spruce**
  - Moisture content at test ~12%
  - Density $\rho_{(\omega \sim 12\%)} = 484 \text{ kg/m}^3$
  - $\lambda_0 = 0.321 \text{ W/(m·K)}$
  - $\lambda_{90} = 0.102 \text{ W/(m·K)}$
  - $R^2 = 0.998$

Results

Guarded hot plate test

- Excellent agreement between experimental data and the respective curve.

- Thermal conductivity of beech and spruce wood at angles to the grain in the longitudinal–radial plane is perfectly represented by the transformation equation for orthotropic materials implemented by the respective rotation of the thermal conductivity tensor.

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Topography image shows a good flatness on the S2-layer and the middle lamella, while minimal dents in the S1-layer are apparent (marked with arrows).

Although, the surface is overall rather flat, two vertical grooves (arrows) are remarkable along the interface S1/CML and S1/S2, respectively.
Scanning probe images from European beech

b) Topography of scan
- Conductivity contrast image shows a clear difference in conductivity between the S2-layer and the middle lamella, with higher conductivity of the S2-layer.

Seemingly increased conductivity is observed along the grooves. Apart from that, the highest conductivity is observed for the S1-layer, followed by the ML and the S2-layer.

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Micro- and SThM-Images from Norway spruce

a) Position of scan

Cross section

20 µm

b) Topography of scan

Topography images on the cross section as well as...

…on the longitudinal section show overall good flatness of the surface with the exception of one groove in each image, marked with arrows along the interface S1/S2.
b) Topography of scan

Apart from effects of topographical features (arrows) on the observed conductivity, the S2-layer shows the greatest conductivity, followed by the ML and the S1-layer.

Contrary, on the image on the longitudinal section the S1-layer shows higher conductivity than the S2-layer and the middle lamella.

c) Thermal data of scan
Results

SThM experiment

Apart from variations in conductivity which are seemingly caused by variations in topography…

The cross section scan on the cell wall of a fiber of European beech and the tracheid of Norway spruce reveals a higher conductivity of the S2 layer compared to the S1 layer and the middle lamella. S1 layer and middle lamella show approximately the same conductivity.

Conductivity S2-layer >>> Conductivity S1-layer ≈ Conductivity ML

In contrast, the respective images from the longitudinal section scan show highest conductivity of the S1-layer, followed by the S2-layer and the middle lamella.

Conductivity S1-layer >>> Conductivity S2-layer >/≈ Conductivity ML
Summary & Conclusions

The guarded hot plate test showed that...

- Thermal conductivity of wood between two principal anatomical directions are perfectly represented by the theoretical curve derived from the respective rotation of the thermal conductivity tensor.

It follows that...

- Wood shows orthotropic symmetry regarding the thermal conduction behavior.
- Thermal conductivity of wood in arbitrary directions can be calculated by this method.

\[
\lambda_{(a1)} = \lambda_L \cdot \cos^2 \alpha + \lambda_R \cdot \sin^2 \alpha \\
\lambda_{(a2)} = \lambda_L \cdot \cos^2 \alpha + \lambda_T \cdot \sin^2 \alpha \\
\lambda_{(a3)} = \lambda_R \cdot \cos^2 \alpha + \lambda_T \cdot \sin^2 \alpha
\]
Summary & Conclusions

The SThM experiment images...

- Differences in thermal conductivity between the individual cell wall layers.
- In cross sections, the S2 shows a higher conductivity compared to the S1 and the middle lamella.
- In contrast, in longitudinal sections thermal conductivity of the S1 layer is apparently higher than conductivity of the S2 layer and the middle lamella.

Explanation

- Assumption of anisotropic thermal behavior of crystalline cellulose, with significant higher thermal conductivity along the cellulose chains compared to conductivity normal to the chains as well as the conductivity of other cell wall materials explains well the observed behavior.
- Vertical oriented cellulose fibrils increase the conductivity of the cell wall layer.
- As visible for the S2-layer in the cross section scan...
- As well as for the S1-layer on the image of a longitudinal section scan.