Determining the thermal conductivity of building materials using the heat flux plate principle

Recording and evaluating with CASSY

Experiment Objectives

- Recording the temperature change as a function of time on a building material plate.
- Qualitative observation of the thermal equilibrium setting.
- Determining the conductivity of a building material plate.

Principles

The thermal conductivity λ is defined as the proportionality constant in the relationship between the thermal flux $\frac{\Delta Q}{\Delta t}$ that crosses the sample and the temperature difference $\Delta \vartheta$ between the sample's two sides:

$$\frac{\Delta Q}{\Delta t} = \lambda \cdot \frac{A}{d} \cdot \Delta \vartheta$$

where d: thickness of the sample
A: surface of the sample.

Unlike electric currents, heat flows have no perfect insulator, so "heat leaks" impede a precise measurement of the thermal flux. The thermal flux does not exactly match the energy flowing in the system.

This experiment determines the thermal conductivity according to the heat flux plate principle, a relative method. This method places one plate on top of another and crosses both with the same thermal flux. The thermal conductivity λ_x of an unknown building material plate (sample) can be calculated using the known value λ_R of a reference plate. The reference plate is also known as the "heat flux plate."

The following applies:

$$\frac{\Delta Q}{\Delta t} = \lambda_x \cdot \left(\frac{A_x}{d_x}\right) \cdot \Delta \vartheta_x = \lambda_R \cdot \left(\frac{A_R}{d_R}\right) \cdot \Delta \vartheta_R .$$

where $\Delta \vartheta_R$ is the temperature difference on the reference plate and $\Delta \vartheta_x$ the temperature difference on the unknown building material plate.

In the experiments, both plates have the same thickness $d_x = d_R$ and the same surface $A_x = A_R$. In this special case:

$$\lambda_x = \lambda_R \cdot \left(\frac{\Delta \vartheta_R}{\Delta \vartheta_X}\right).$$

In each case, the temperatures

- on the outside of the top building material plate (here ice) ϑ_o,
- between the two building material plates ϑ_m, and
- on the underside of the bottom building material plate ϑ_u, i.e. the chamber's inside temperature

are measured.

Fig. 1: Experiment setup: Determination of the thermal conductivity using the heat flux plate principle.

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Apparatus

1 Calorimetric chamber 389 29
1 Building materials for calorimetric chamber... 389 30
1 Transformer 2 to 12 V; 120 W 521 25
1 Sensor-CASSY 2.. 524 013
1 CASSY Lab 2 .... 524 220
2 NiCr-Ni Adapter S, Type K 524 0673
3 Temperature probe NiCr-Ni, 1.5 mm, Type K 529 676
2 Connecting lead 32 A, 100 cm, black............ 501 33
Ice
Thin plastic film
1 PC with Windows XP/Vista/7/8

There are two distinct cases.

If the reference plate is on the bottom, then

$$\Delta\vartheta_R = \vartheta_u - \vartheta_m \quad \text{and} \quad \Delta\vartheta_x = \vartheta_m - \vartheta_o.$$

The thermal conductivity of the unkown building material plate thus results in

$$\lambda_x = \lambda_R \cdot \left(\frac{\vartheta_u - \vartheta_m}{\vartheta_m - \vartheta_o}\right).$$

If the reference plate is on top, then this results in:

$$\lambda_x = \lambda_R \cdot \left(\frac{\vartheta_m - \vartheta_o}{\vartheta_u - \vartheta_m}\right).$$

The formulas used are valid in the thermal equilibrium, i.e. in stationary condition, in which the temperature is constant over time at every point.
The system is not in thermal equilibrium right after switching the hot plate on. To maintain the temperature difference in thermal equilibrium, record the inside temperature's progression over enough time (in the magnitude of 1.5 hours). The temperature's change over time is proportional to the temperature plus a constant:

$$\frac{\Delta\vartheta}{\Delta t} = a \cdot \vartheta + b.$$

This equation's solution for the temperature as a function of time ϑ (t) is:

$$\vartheta(t) = \vartheta_{TE} - \vartheta_{Diff} \cdot e^{-\frac{t}{\tau}}$$

where:

- ϑ_{TE}: temperature in thermal equilibrium
- $\vartheta_{Diff} = \vartheta_{TE} - \vartheta_{Begin}$: temperature difference
- τ: time constant

The temperature in thermal equilibrium on the heated side of the building material sample, or that between the two plates, adapting the function from the form

$$f(x) = A–B\cdot\exp(-x/C)$$

produces the values recorded in the experiment. The parameter A obtained by this adapation then corresponds exactly to the desired temperature ϑ_{TE}. Then it is equal to ϑ_u or ϑ_m.

The ice keeps the outside temperature on top of the top building material plate low and above all constant. Since there can nevertheless be small temperature fluctuations, the outside temperature's values are averaged, and then this average ϑ_o comes into the calculation of the temperature difference.

Setup

The experiment's setup is represented in Fig. 1.

Remark: Face the particle board and the Rohacell plate inward, i.e. toward the hot plate. By contrast, face the Fermacell plate outward, i.e. toward the ice.

- Insert the hot plate into the calorimetric chamber.
- Prepare two building material plates, assembling them like a sandwich, for subsequent placement in the calorimetric chamber:
- Insert an aluminum contact disk into the circular notch intended for this purpose on the inner building material plate at the end of the groove using heat conductive paste. In doing so, the contact disk must be turned so the notch is in line with the groove.
- Only apply the heat conductive paste on the contact disk.
- Carefully, i.e. without bending it, place a thin aluminum plate (0.3 mm thick) with the black side facing outward on the side of the building material plate prepared with heat conductive paste, and press the two together.
- Repeat this step for the other side, but use an aluminum plate without lacquer coating (0.5 mm think). The aluminum plate without lacquer coating then goes between the two building material plates.
- Once again, place a thin aluminum plate on the outer building material plate and press them together.
- Now insert the plate covered with aluminum on both sides into the calorimetric chamber with the side with black lacquer toward the bottom. It should be noted that the places where the temperature sensors will be inserted (the groove ends) must be turned toward the calorimetric chamber's side with two openings.
- Then place the plate covered with aluminum on one side on the plate already inserted into the calorimetric chamber with the black side toward the top.
- It should be noted that the aluminum plate without lacquer coating goes between the building material plates and that the places where the temperature sensors for the two building material plates will be inserted (the groove ends) are twisted by 180°.
- First, carefully, i.e. without bending it, push the temperature sensor's tip through the rubber stopper's hole (1.5 mm diameter). Do not put it in the calorimetric chamber yet!
- Place the temperature sensor on the top and bottom sides as well as between the two building material plates. If needed, raise the building material sample somewhat using the mounting hook.
- Connect the temperature sensor to Sensor-CASSY using the NiCr-Ni Adapter S, as shown in Fig. 1.
- Connect the transformer to the hot plate's connections. Do not turn on the transformer yet!
- Cover the calorimetric chamber with a thin but water-tight plastic film (e.g. plastic wrap). Lay a bag of ice cubes on top of the aluminum plate. Make sure no water can enter the chamber or come in contact with the cables.

Remarks: The bag may not be too small. The ice must contact the aluminum plate as well as possible. The smaller the ice cubes, the better the ice lies on the building material sample. A heavy object that can be placed on the bag without damaging it is also helpful.

Carrying out the Experiment

Safety note

Do not heat the calorimetric chamber, the wall materials or the building material plates beyond 60 °C!

- Load the settings in CASSY Lab 2.

Remark: If necessary, correct the temperature sensors before inserting them into the measuring chamber at the same temperature – e.g. in still water – in CASSY Lab 2, i.e. bring them to display the same temperature.

- Switch the transformer on. Do not start the measurement yet.
- Observe temperatures ϑ_{A11}, ϑ_{A12} and ϑ_{B11}.

Remark: Depending on the ice's temperature, it can very well be significantly below 0 °C. To keep this temperature as constant as possible during the measurement, it is recommended that the temperature be between -2 °C and +4 °C.

- Wait until the lowest temperature stops changing.
- Start the measurement with ⏱.
- The inside temperature rises, while the outside temperature under the ice remains constant. The space between the two building material plates is exposed to both effects. Empirically, the average temperature falls before rising toward the end of the measurement.
- If the outside temperature rises (already at a difference of 0.5 °C), fix the contact with the ice. If necessary, repeat this correction during the measurement.
- If the inside temperature reaches 60 °C, switch the transformer off and repeat the experiment with a lower voltage or power.
- If the inside temperature changes only slowly or stops changing (to about 0.15 °C per minute), the measurement can be stopped with ⏱.
- Switch the transformer off.

Remark: During disassembly, remove the temperature sensors first. Only thereafter can the building material sample be lifted out, using the mounting hook.

Measurement Example

Fig.s 2 through 5 represent the progressions of temperature over time for the various building material plates. The temperatures ϑ_u and ϑ_m in thermal equilibrium are determined from the curves of the inside temperature (the top curve in each case) and of the average temperature (the middle curve in each case) by adaptation. The continuous line is precisely the function obtained from the adaptation. The average of the outside temperature (the bottom curve in each case – ice) produces the temperature ϑ_o. This serves in calculating the temperature differences $\Delta\vartheta_R$ and $\Delta\vartheta_x$.

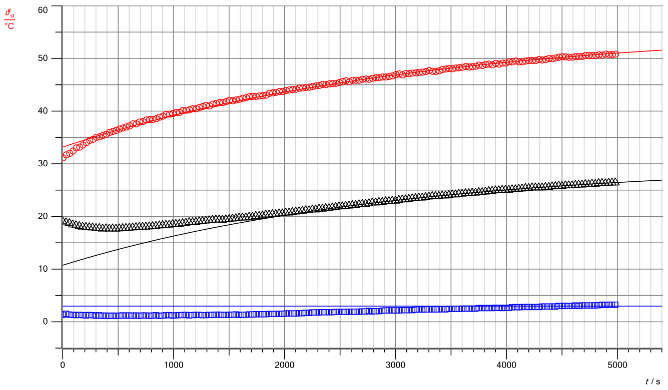

Fig. 2: Both building material samples made of polystyrene.

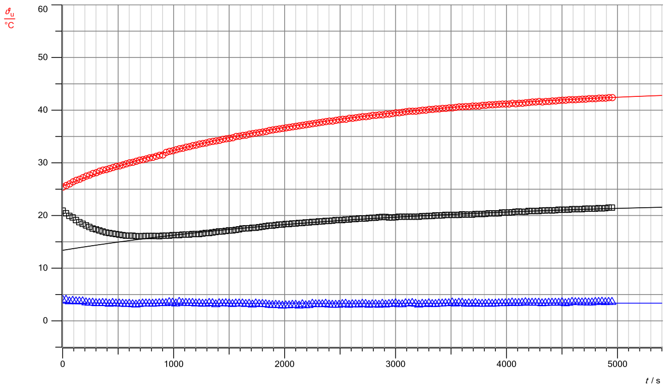

Fig. 3: Bottom building material sample made of wood chips.

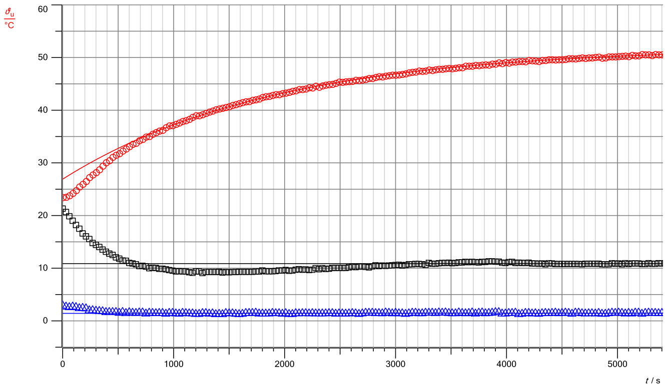

Fig. 4: Bottom building material sample made of Rohacell (insulating foam)

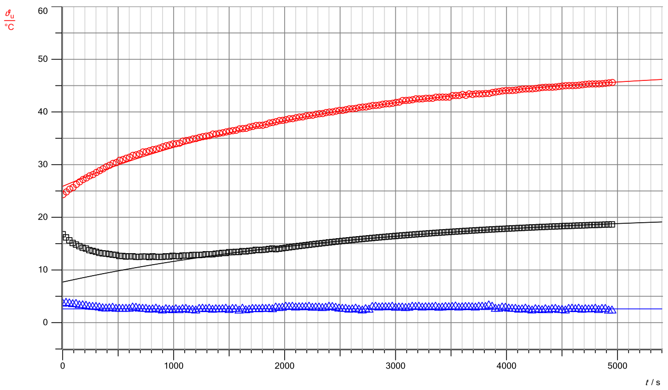

Fig. 5: Top building material sample made of Fermacell (gypsum plaster)

Evaluation

In these experiments, the heat flux plate is in each case made of polystyrene with thermal conductivity

$$\lambda_R = 0.17\ \frac{W}{m\,K}.$$

Table 1: Readings with the end temperatures extrapolated from the curves

Unknown plate	Poly-styrene	Chips	Rohacell	Fermacell
$\frac{U}{V}$	8	8	6	8
Outside	Ice			
$\frac{\vartheta_o}{°C}$	3	3	1	3
Top plate	Poly-styrene	Poly-styrene	Poly-styrene	*Fermacell*
$\frac{\vartheta_m}{°C}$	30	23	11	21
Bottom plate	Poly-styrene	*Chips*	*Rohacell*	Polysty-rene
$\frac{\vartheta_u}{°C}$	56	45	52	49
Inside	Calorimetric chamber with hot plate			

Table 2: Calculation of the thermal conductivity

$\frac{A}{m^2}$	0.0225			
$\frac{d}{m}$	0.01			
$\frac{\lambda_R}{\frac{W}{m \cdot K}}$	0.17 (polystyrene)			
$\frac{\Delta\vartheta_R}{K}$	27 (26)*	20	10	28
$\frac{\Delta\vartheta_x}{K}$	26 (27)*	22	41	18
	Poly-styrene	*Chips*	*Rohacell*	*Fermacell*
$\frac{\lambda_x}{\frac{W}{m \cdot K}}$	0.18 (0.16)*	0.15	0.04	0.26
$\frac{\lambda_H}{\frac{W}{m \cdot K}}$	0.16-0.18	0.07-0.17	0.02-0.05	0.23-0.28

* The values in brackets refer to when the bottom polystyrene plate is considered the reference plate.

The values for λ_H come from the manufacturer.

Comment

The derivation of the formula

$$\lambda_T = \lambda_R \cdot \left(\frac{\Delta\vartheta_R}{\Delta\vartheta_X}\right)$$

assumes the same amount of heat crosses both building material plates. But since there are small, inevitable heat losses between the two building material plates, the actual thermal conductivity λ_T has the relationship

$$\lambda_T = \lambda_R \cdot \left(\frac{\Delta\vartheta_R}{\Delta\vartheta_X}\right)\left(\frac{\dot{Q}_R}{\dot{Q}_X}\right) = \lambda_x \left(\frac{\dot{Q}_R}{\dot{Q}_X}\right),$$

where $\dot{Q}_R$ is the heat through the reference plate and the $\dot{Q}_X$ the heat through the unknown building material plate. The thermal conductivity λ_x is thus the calculated thermal conductivity (Table 2). Therefore:

$$\lambda_x = \lambda_T \left(\frac{\dot{Q}_X}{\dot{Q}_R}\right).$$

Since the heat flows out from inside the calorimetric chamber, the heat crossing the inner building material plate is greater than the heat crossing the building material plate above.

If the reference plate is above (i.e. here in the case of the Rohacell plate and the particle board), then $\dot{Q}_X > \dot{Q}_R$ and the measured thermal conductivity λ_x turns out to be greater than the actual thermal conductivity λ_T.

By contrast, the measured thermal conductivity is somewhat smaller than the actual thermal conductivity if the reference plate is inside (here in the case of the Fermacell plate).

LD DIDACTIC GmbH . Leyboldstrasse 1 . D-50354 Huerth / Germany . Phone: (02233) 604-0 . Fax: (02233) 604-222 . E-mail: info@ld-didactic.de