Related topics

Heat transition, heat transfer, heat conductivity, thermal radiation, hothouse effect, thermal capacity, temperature amplitude attenuation.

Principle and task

A model house with replaceable side walls is used for determining the heat transition coefficients (*k* values) of various walls and windows and for establishing the heat conductivities of different materials. For this purpose the temperatures on the inside and outside of the walls are measured at a constant interior and outer air temperature (in the steady state).

With a multilayer wall structure the temperature difference over a layer is proportional to the particular thermal transmission resistance. The thermal capacity of the wall material affects the wall temperatures during heating up and temporary exposure to solar radiation.

Equipment

High insulation house	04507.93	1
Thermal regul. f. high insul. house	04506.93	1
Partitions, plastic foam, 5 off	44536.02	1
Lamp socket E27, mains conn.	06751.00	1
Filament lamp, 220 V/120 W, w. refl.	06759.93	1
Temp. meter 2× NiCr-Ni, hand-held	07140.00	2
Thermocouple NiCr-Ni, 500 C max.	13615.02	4
Tripod base -PASS-	02002.55	1
Stopwatch, digital, 1/100 sec.	03071.01	1

Problems

1. Measurement and interpretation of water temperatures during the heating up and during temporary external illumination of the walls.
2. Determination of the heat conductivities of wood and Styropor.
3. Determination of the *k* values of ordinary glass and insulating glass windows and of wooden walls of different thicknesses, and of walls with wood, Styropor or cavity layers.

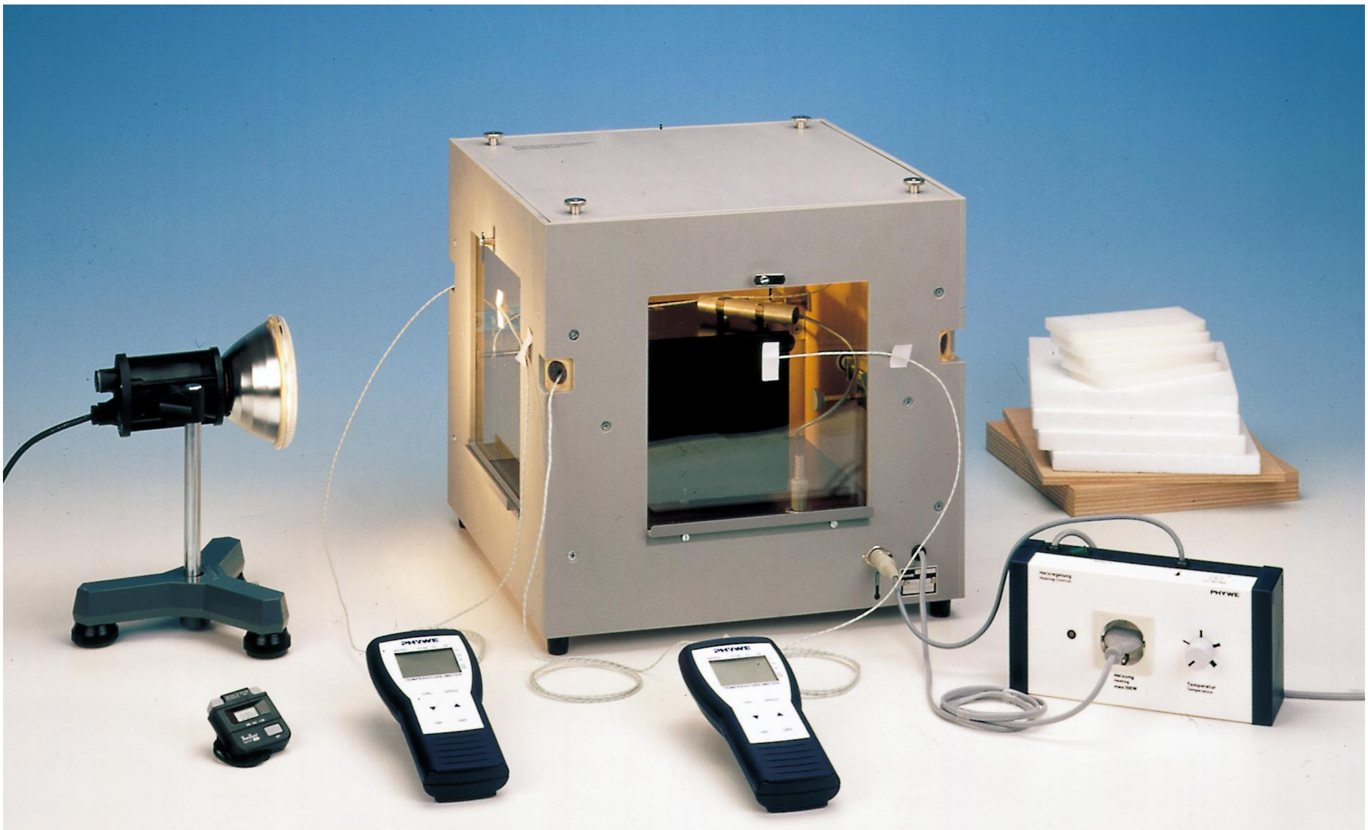
Set-up and procedure

Since the measured temperature differences play a part in the evaluation of the experimental results, the agreement of the thermocouples must be checked and any deviations taken into account in the evaluation.

Eight different walls and windows are examined in two measurement series each lasting about 1.5 h. Inner and outer wall and air temperatures have to be measured in each case and in addition the temperatures between the layers in the case of a multilayer wall structure.

Since there will be a temperature gradient from the top downwards in any house, all temperature measurements have to be recorded at the same height. Holes in the corner posts of the model house are used for the insertion of thermocouples to measure the interior and inside wall temperatures. The thermocouple used for measurement of the interior temperature projects about 5 cm into the house.

Fig. 1: Experimental set-up: Heat insulation / Heat conduction.



For measurement of the wall temperatures, the tip of the thermocouple should be firmly secured at the level of the lateral holes and as close as possible to the perpendicular centreline of the wall. The leads must also be secured to the house structure to ensure strain relief.

A 100 W incandescent lamp with a covering cap is used for heating purposes, the interior temperature being kept virtually constant by a heating thermostat. The temperature sensor of the thermostat is secured to the covering cap of the incandescent lamp and connected to the thermostat by means of a 5-pin socket on the floor and on the side of the house. The power supply for heating is introduced via the thermostat plug. The temperature switch is set on the fourth graduated division, thus producing in the steady state an internal temperature in the room of about 60°C.

1. The following walls and windows are used for the first series of measurements:
   – wood, *d* =1 cm in thickness,
   – wood, *d* = 2 cm in thickness,
   – Styropor, *d* = 2 cm in thickness (large 25×25 cm panel),
   – ordinary glass.

The windows are in this case set in a wooden wall, *d* = 1 cm in thickness.

During the heating-up phase:

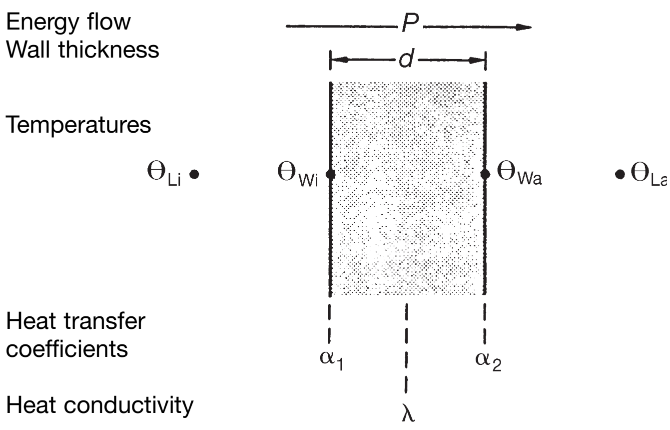
Measurement of the inside and outside wall temperatures on the wood (*d* = 2 cm) and Styropor (*d* = 2 cm) at intervals of about 5min. After 30 min, illuminate in succession the wooden wall (*d* = 2 cm), the Styropor wall and the glass window for 5 mm with a 150 W incandescent lamp from a distance of about 15 cm, leaving in each case a 5 min interval between illumination phases. Temperature measurements to be recorded at minute intervalls. While the window is illuminated, remove the thermocouple from the outer side of the wooden wall and use it to measure the interior temperature.

After about 70 min heating time (steady state): Measure the inside and outside wall temperatures of the Styropor wall over a period of about 5 min, taking particular note of the effect of the connection and disconnection of the heating. Withdraw the thermocouple measuring the interior temperature and use it for measurement of the external air temperature, then resecure it to the outside of the woodenwall, *d* = 2 cm. Measure the inside and outside wall temperatures on the wooden wall (*d* = 2 cm) during a period when the heating is connected. Open the cover of the model house and reposition the inside wall thermocouples on the wood (*d* = 1cm) and glass sections, then close the cover. Reposition the outside wall thermocouples on the wood (*d* = 1 cm) and glass sections.

Wait about 15 min, measure the wall temperatures, then check the internal and external air temperatures.

2. The following walls and windows are used for the second series of measurements:
   – multilayer wall consisting of 2 cm Styropor (inside) and 2 cm wood (outside),
   – multilayer wall consisting of 1 cm wood (inside) 1 cm cavity layer (with a narrow foam strip at the edge) and 2 cm Styropor (a small 21×21 cm panel, inserted in the opening of the wall from the outside)
   – wooden wall, *d* = 3 cm in thickness,
   – insulating glass windows.

Fig. 2: Heat energy flow through a wall.
Internal and external air and wall temperatures: Θ_{Li}, Θ_{La}, Θ_{Wi}, Θ_{Wa}.



First of all measurements are recorded at four points on the wall with the cavity layer: on the wood, on the room side; on the wood, on the cavity layer side; on the Styropor, on the cavity layer side; on the Styropor, on the outside. Care is required while securing the thermocouples, to prevent folding.

After about 70 min heating time (steady state):

The temperatures at the four points on the wall with a cavity layer are kept under observation and measured over a period of a few minutes.

Open the cover of the house and reposition the thermocouples on the multilayer wood/Styropor wall, loosing the tensioning screws as far as necessary and retightening. Measure the temperature at the following three points: on the Styropor, on the room side; at the contact surface between wood and Styropor; on the wooden wall, on the outside. Then close the cover. The fourth thermocouple is used for air temperature measurements. Wait for about 15 min, measure the wall temperature, then measure the internal air temperatures (mean value over the heating period) and the outer air temperatures.

Open the cover of the house and use two thermocouples for measuring the inside wall temperatures of the wooden wall (*d* = 3 cm) and of the insulating glass windows. Close the cover. The other two thermocouples are placed on the outside of the wooden wall (*d* = 3 cm) and on the insulating glass window. Wait about 15 min and measure the wall temperatures.

Theory and evaluation

The thermal energy flow *P* through a homogeneous, flat wall is determined in the steady state (permanent state) by means of the air-wall heat transfer and the heat conduction in the wall. The energy flow is governed by the surface area of the wall *A* and the particular temperature differences:

Air-wall heat transfer, internal
(α_i = internal heat transfer coefficient)

$$P = \alpha_i \cdot A \cdot (\Theta_{Li} - \Theta_{Wi}) \quad (1)$$

Wall-air heat transmission, external
(α_a = external heat transfer coefficient)

$$P = \alpha_a \cdot A \cdot (\Theta_{Wa} - \Theta_{La}) \quad (2)$$

Heat conduction in the wall
(d = thickness, λ = heat conductivity)

$$P = \frac{\lambda}{d} \cdot A \cdot (\Theta_{Wi} - \Theta_{Wa}) \qquad (3)$$

Rearrangement and summation of these three equations yields

$$P = k \cdot A\ (\Theta_{Li} - \Theta_{La}) \qquad (4)$$

in which k = heat transition coefficient or k value.

The following formula then applies

$$\frac{1}{k} = \frac{1}{\alpha_i} + \frac{1}{\lambda} + \frac{1}{\alpha_a} \qquad (5)$$

The parameter

$$\Delta = \lambda/d \qquad (6)$$

which is governed only by the material and thickness of the wall is known as the thermal transmission coefficient.

The reciprocals α, k and A are thermal resistance values which are designated the heat transfer resistance, the heat transition resistance and the heat transmission resistance. In a wall consisting of successive layers, equation (3) applies as appropriate to all layers, so that the sum of the heat transmission resistance has to be inserted in equation (5).

$$\frac{1}{k} = \frac{1}{\alpha_i} + \frac{1}{\Lambda_1} + \frac{1}{\Lambda_2} + \dots \frac{1}{\Lambda_n} + \frac{1}{\alpha_a} \qquad (7)$$

The phenomena participating in the transfer of heat through a layer of air are the conduction, convection and radiation. Equation (6) yields an approximate value for the heat transmission coefficient of a vertical air layer between non-metallic walls only in the case of small thicknesses (d < 5 mm). With an increase in the thickness it is mainly determined by the radiation fraction which, in the case of parallel surfaces, is independent of the distance between them. With layer thicknesses in excess of 5 cm the convection process causes a reduction in the resistance.

Our consideration of the problem has up to now dealt with the steady state. The heating and cooling of a wall accompanying a change of solar radiation is determined by the heat storage capacity C of the wall:

$$C = c \cdot m \qquad (8)$$

in which c = specific thermal capacity,
m = mass of the wall.

Temperature variations on the outside should be reflected as little as possible on the inside. A smaller temperature amplitude on the inside wall is in general accompanied by a correspondingly large phase displacement.

The wood and Styropor wall temperatures recorded during the heating up phase, showed wooden walls of identical thickness to have a higher heat storage capacity. In the Styropor wall steady-state temperatures were reached even after 20 min.

Short-term illumination of the walls gives rise to a very high temperature on the outside wall (heating from about 30° to about 80°C). In the Styropor wall the heating is transmitted with only a very slight time-lag (about 2 min) and a low amplitude to the inner wall (heating by about 7 K). After disconnection of the lamp, the temperatures on both the inside and the outside fall to the initial values within 5 min.

During illumination of the wooden wall the temperature on the inside only rises appreciably after about 2 min, reaching the peak value after a further 8 min. Since the steady-state temperature of the wooden wall has not yet been reached, only a very slight fall in the inside wall temperature occurs on conclusion of the illumination period. The temperature of the outside wall falls back slowly after disconnection of the lamp, reaching the end temperature only after about 30 min.

The entry of light through the window causes the interior temperature to rise initially by about 5 K. The heating comes into operation very much less frequently if at all, so that cooling occurs and the room temperature again falls. A heating of 1–2 K is observed on the inside of wooden and Styropor walls.

In the steady state the interior temperature may vary by about 2 K as a result of the thermostatically controlled heating; it

Table 1

Temperatures of air and insulating materials as well as the values of k and the conductibilities of different insulating materials and windows.		Θ_{Li} / °C	Θ_{La} / °C	Θ_{Wi} / °C	Θ_{Wa} / °C	P/A / W/m^2	k / W/Km^2	λ / W/Km
Styropor,	2 cm	55.3	22.3	51.6	27.7	44	1.3	0.037
Wood,	1 cm	55.3	22.3	45.1	35.1	109	3.3	0.12
Wood,	2 cm	55.3	22.3	47.3	34.0	95	2.9	0.14
Wood,	3 cm	58.1	23.0	49.1	32.2	75	2.1	0.13
Glass,	5 mm	55.3	22.3	40.7	39.4	139	4.2	0.53
Insulating glass		58.1	23.0	48.7	34.5	93	2.7	–

Values taken from the literature for the thermal conductivites of the materials used:

Wood (spruce, plywood)	λ = 0.14 W/Km
Polystrene expanded foam, Bulk density 15–30 kg/m^3	λ = 0.035–0.041 W/Km
Glass	λ = 0.7–1 .1 W/Km

also rises by a further 2 K/h after 1 h heating time, so that the interior temperature is slightly higher during the second series of measurements. Measurement of the inside wall temperatures of Styropor walls may reveal a variation of about 0.5 K in parallel with variations in the air temperature, the variation in other types of wall being only 0.1 K (corresponding to 1 digit on the dial).

The thermal energy flow through a wall is determined from the difference in the outside wall and the outside air temperature. The heat transfer coefficient in the case of natural air movement in enclosed rooms is for all wall materials encountered in practice

$$\alpha = 8.1 \text{ W/Km}^2$$

Course of the calculation:

Equation (2) yields *P/A*

Equation (4) yields *k*

Equation (3) yields λ

Table 1 contains all the calculated data and measurement results for homogeneous walls and for windows.

The bulk density of the Styropor wall used for this purpose is 20 kg/m^3. Determination of the thermal conductivity of glass involves a serious error, since the temperature difference across the wall is small.

Equation (5) indicates a linear connection between the heat transition resistance 1/*k* and the wall thickness *d,* which is reproduced in Fig. 3. The intercept of the axis for *d* = 0 is equal to the sum of the internal and external heat transfer reistance $1/\alpha_i + 1/\alpha_a$; it is obtained by extrapolation of the measurement values for wood (in the model house $\alpha_i > \alpha_a$ as a result of the radiation of heat to the walls from the large radiator). The measurement for Styropor has been entered in the graph in order to make this clear.

The greater the thermal conductivity, the less steep will be the curve. In the case of good heat conductors, the main factor contributing to heat insulation is the heat transfer reistance (due merely to the presence of a wall). The thickness of the wall exerts a considerable influence on the heat transition resistance, especially in the case of bad heat conductors (insulating materials).

The heat transmission coefficient for a vertical layer of air in a wall is calculated from equations (3) and (6) in the following form:

$$\frac{1}{\Lambda} = \frac{\Delta\Theta \cdot A}{P} \qquad (9)$$

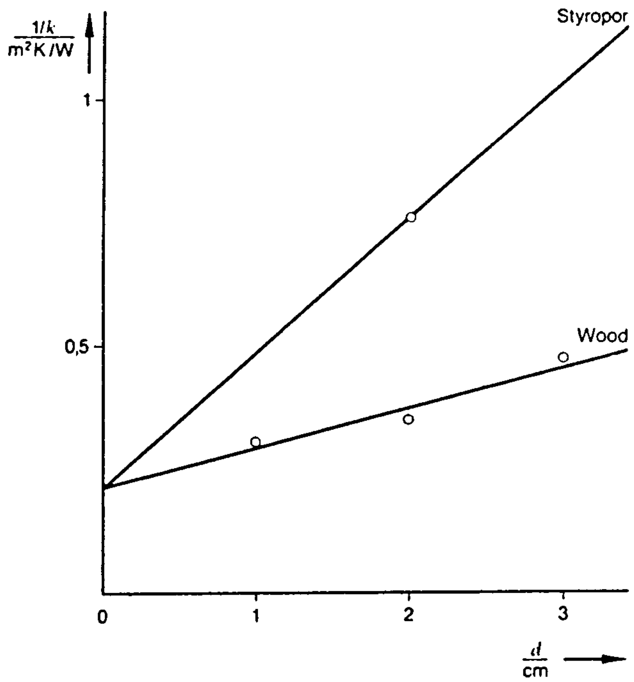
in which $\Delta\Theta$ denotes the temperature difference over the air layer and *P/A* is determined from equation (2).

The measurements on the wood/Styropor wall with a cavity layer yield the following:

$$\frac{P}{A} = 8.1 \frac{\text{W}}{\text{Km}^2} \cdot (27.8°\text{C} - 23.0°\text{C}) = 39 \text{ W/m}^2$$

$$\frac{1}{\Lambda} = \frac{(50.1°\text{C} - 45.1°\text{C})}{39 \text{ W/m}^2} = 0.13 \frac{\text{Km}^2}{\text{W}}.$$

Fig. 3: Heat transition resistance 1/*k* as a function of the wall thickness *d.*



Literature value for an air layer 1 cm in thickness:

$$\frac{1}{\Lambda} = 0.14 \frac{\text{Km}^2}{\text{W}}.$$

On a multilayer wall the ratio of the temperature differences is equal to the inverse ratio of the heat transmission resistances:

$$\frac{\Lambda_2}{\Lambda_1} = \frac{\Delta\Theta_1}{\Delta\Theta_2}. \qquad (10)$$

This expression is frequently used in conjunction with a heat measuring plate having a known heat transmission coefficient to determine the thermal conductivity value of other materials.

Using equation (10), we obtain for the wood/Styropor walls with layers of identical thickness *d,* used in the experiment:

$$\frac{\Delta\Theta_{\text{wood}}}{\Delta\Theta_{\text{Styropor}}} = \frac{\lambda_{\text{Styropor}}}{\lambda_{\text{Wood}}}. \qquad (11)$$

Assuming λ_{wood} to be a known quantity, the measurement yields the following value:

$$\lambda_{\text{Styropor}} = \frac{34.3°\text{C} - 28.2°\text{C}}{55.4°\text{C} - 34.3°\text{C}} \cdot 0.14 \text{ W/Km} = 0.040 \text{ W/Km}.$$