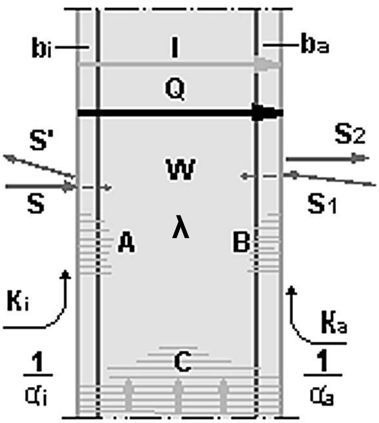
3.2. Structural statics sensors

3.2.1 Basic principles of measuring heat flow

The thermal transmittance characteristic of any structural element is determined by certain complex relationships; it depend inter alia on the thermal conductivity of the materials used, on the thickness of its various component layers, on its structural geometry (e.g. flat or cylindrically curved walls, etc.), and on the ambient conditions at the structure's surfaces inside and outside.

Factors influencing the heat flow through a wall:



Q = Heat flow through the wall
I = Water vapor, diffusion
λ = Thermal conductivity
1/α = Thermal surface transfer resistance (inside and outside)
b = Thermal penetration coefficient (1 to 2 cm, inside and outside)
S = Thermal radiation onto and off the wall (1 to 2 mm)
A = Condensation from inside
B = Moisture from outside (e.g. rainfall)
C = Moisture in the brickwork (capillarity and diffusion)
W = Thermal energy storage capacity
K = Convection (inside and outside)

3.2.2 Thermal transmittance coefficient (U) - physical units and relationships

The thermal transmittance coefficient (***U*** value) of a structural element describes the quantity of thermal energy that passes through it from one side to the other (no matter how many layers) per second and per square meter surface at a constant difference in ambient temperature inside / outside of 1ºK.
A structure's U value (unlike its thermal conductance $\boldsymbol{\Lambda}$) includes the thermal transfer characteristics at its surfaces ($\boldsymbol{\alpha_i}$ and $\boldsymbol{\alpha_o}$), i.e. the intensities of thermal transfer at the structure's boundary surfaces inside and outside.
A structure's thermal transmittance coefficient (***U***) is the reciprocal of its total thermal transmittance resistance ($\boldsymbol{R_k}$);
RK is the sum of the thermal conductance resistances (***R***) of the structure's various contiguous layers plus the thermal surface transfer resistances ($\mathbf{R_i}$, $\mathbf{R_o}$) between the structure and the ambient media on either side (e.g. air):

$$U = \frac{1}{R_K} = \frac{1}{(R_i + R + R_a)} = \frac{1}{\left(\frac{1}{\alpha_i} + \frac{1}{\Lambda} + \frac{1}{\alpha_a}\right)}$$

U = Thermal transmittance coefficient [W/m²K]
R_k = Total thermal transmittance resistance [m^2K/W]
R_i = Thermal surface transfer resistance, inside the structure [m^2K/W]
R_a = Thermal surface transfer resistance, outside the structure [m^2K/W]
R = Thermal conductance resistances (of each layer) [m^2K/W]
α_i = Thermal surface transfer coefficient, inside [W/m^2K]
α_a = Thermal surface transfer coefficient, outside [W/m^2K]
Λ = Thermal conductance coefficient [W/m^2K]

Thermal transmittance resistance	=	Thermal conductance resistances of material layers + thermal surface transfer resistances	$R_k = R + Ri + Ra$
Thermal conductance resistance	=	1 / Thermal conductance coefficient	$R = 1 / \Lambda$
Thermal surface transfer resistance	=	1 / Thermal surface transfer coefficient	$R_i = 1 / \alpha_i$, $R_a = 1 / \alpha_a$
Thermal transmittance resistance	=	1 / Thermal transmittance coefficient	$R_k = 1 / U$

3.2.3 Heat flow density (q) - physical units and relationships

An external structure in a state of general equilibrium is bordered on its one side by inside air at temperature ($\boldsymbol{T_{Li}}$) and on its other side by outside air at temperature ($\boldsymbol{T_{Lo}}$); through this component passes a heat flow of density “q”. The heat flow density can be calculated according to the following formula :

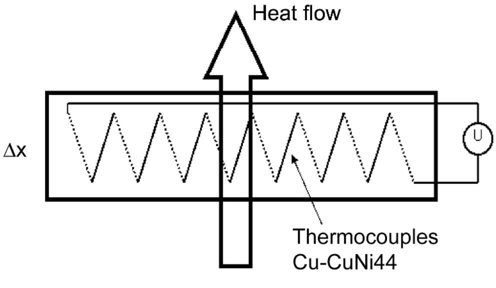
$$q = U(T_{Li} - T_{La})$$

U = *Thermal transmittance coefficient [W/m²K]*
q = *Heat flow density [W/m²K]*
T_{Li} T_{La} = *Temperature of air, inside Temperature of air, outside [°C]*

3.2.4 Measuring principle, heat flux sensor plates (wall for measuring thermal transmittance (U value))

Heat flux plates are highly sensitive sensors permitting precise measurement of heat flow densities (***q***) (**= energy per time and surface**).

A heat flux sensor plate laid on the measuring point to be tested generates a resistance to the heat flow it thus restricts. As heat passes through the thickness of the plate a temperature gradient is formed proportional to the density of the heat flow.



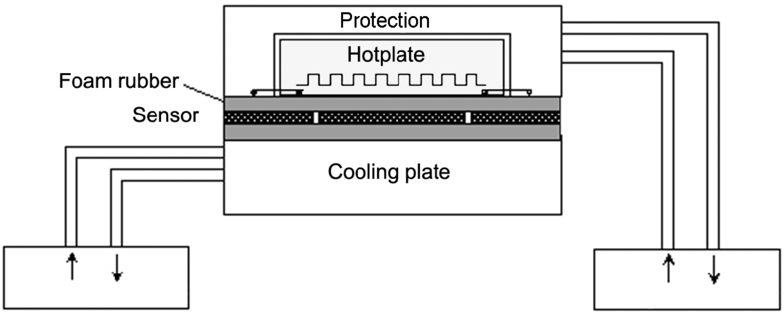
Heat flux sensor plates comprise a meander array of numerous inversely connected thermocouples embedded in a substrate. The substrate materials are thick and the plates are designed with a protective ring round the meander array to stop the heat flow from circulating

too freely there at the sides. The heat flow values obtained always refer to the surface covered by the meander array; they are averaged over this surface.
These active sensors provide signals in the millivolt range that can be evaluated fairly easily.
The heat flow density (***q***) is obtained by multiplying the measured DC voltage (***Uth***) with a calibration constant (***C***); C is determined individually per case, usually based on a single-plate device.

$$q = C\,U_{th}$$

q = *Heat flow density [W/m²K]*
C = *Calibration constant [W/m²mV]*
Uth = *Measured voltage [mV] [mV]*

Calibration
Calibration is performed at a mean temperature of 25 °C and a heat flow density of approx. 100 W/m2. For this purpose the sensor is embedded between two foam rubber panels.
Schematic diagram showing the structure of the plate device



If the customer so requests calibration can be performed at any other specified mean temperature between 10 and 50 °C.
The level of reproducibility for calibrations performed in this way is better than 1%. The level of uncertainty affecting the calibration value of sensors is guaranteed within 5% for the duration of one year.

☞ ***Since calibration values can be adversely affected by ageing, thermal stress, and the diffusion of impure gases and water, it is recommended that sensors be recalibrated at regular intervals (approx. 1 year).***

Calibration results should be documented in a test report; this should be included with each heat flow plate as part of standard delivery.

3.2.4.1 Model variants

ALMEMO® heat flux plates
The calibration value for ALMEMO® heat flux plates FQ A0xx will have been stored in the ALMEMO® connector before leaving our factory so that these ALMEMO® devices should already indicate the current heat flow density in W/m²; (see Figure). However, this calibration value can also be scaled by the user according to the following table:

Heat flow density, maximum measuring range [W/m²]	Calibration value [W/m²mV]	Measuring range	Factor	Exp.
0.0 to 5200.0	1.0 to 20.0	260 mV	0.100-2.000	1
0.0 to 5200.0	10.0 to 200.0	26 mV	0.100-2.000	2

3.2.4.2 Use of heat flux plates

Heat flux plates are used in a wide variety of areas in the natural sciences and applied technology.

1. To determine heat loss through walls in buildings, pipework, cold stores, heat storage systems.
2. Calorimetry, measuring the thermal characteristics of substances.
3. Technical applications in which temperature difference is used as a control variable.

3.2.5 Measuring principle in determining thermal transmittance coefficients (U value)

The measuring principle involved in quantifying heat transmittance loss at partition elements, e.g. walls, heating system components, etc., is based on the method that uses a heat flux sensor plate fitted directly in the plane of thermal transfer. From the sensor's known thermal characteristics and the thermo-electrically measured temperature difference it is then possible to determine the heat flow density (***q***) of the loss.
By also measuring the surface temperatures on either side of the structural element and the air temperatures immediately inside and outside it is then possible to calculate all the relevant thermal coefficients.
In practice these formulae are of only limited use because they are only valid in a state of general equilibrium (i.e. temperature relationships remaining constant through time, the wall emanating precisely the same amount of heat as it absorbs, and the wall's heat storage capacity being of no significance).
And the temperatures must be defined exactly.
Calculations are based therefore on the cyclic acquisition of average values for temperature and heat flow density.
Given a sufficiently long measuring period any influence that the structure's heat storage capacity may have on these calculations (e.g. the U value) will become negligibly small and the calculated average value will certainly come very close to the structure's actual U value, e.g. of the wall.
The quotient q/T1-T0 will, depending on how the temperature sensor is used, produce the thermal transfer coefficients (***α***i, ***α***a), the thermal conductance coefficients (***Λ***), or the thermal transmittance coefficients (***U***) - or the corresponding reciprocal values; (see Table 3.2.2.):

(see Table 3.2.2.)

$$\text{Thermal surface transfer coefficient } \alpha_i = \frac{(\text{Heat flow density q})}{(\text{Wall temp., inside } T_{Wi} - \text{Air temp., inside } T_{Li})}$$

$$\text{Thermal surface transfer coefficient } \alpha_a = \frac{(\text{Heat flow density q})}{(\text{Wall temp., outside } T_{Wa} - \text{Air temp., outside } T_{La})}$$

$$\text{Thermal conductance coefficient } \Lambda = \frac{(\text{Heat flow density q})}{(\text{Wall temp., inside } T_{Wi} - \text{Wall temp., outside } T_{Wa})}$$

Experimental U value:

$$\text{Thermal transmittance coefficient } U = \frac{(\text{Heat flow density q})}{(\text{Air temp., inside } T_{Li} - \text{Air temp., outside } T_{La})}$$

Example 1
*The thermal conductance resistance (**R**) - decisive as regards the thermal insulation characteristics of a wall - can be derived from the measured inside and outside surface temperatures and the heat flow density (**q**):*

$$q = \frac{1}{R}(T_{Wi} - T_{Wa})$$

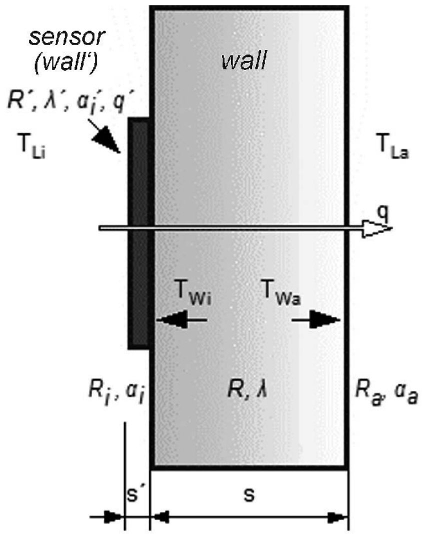
Example 2
*The thermal conductance resistance (**R**) can also be derived from the U value, if this is known or has been measured:*

$$R = \frac{1}{U} - \frac{1}{\alpha_i} - \frac{1}{\alpha_a}$$

*In this case the thermal transfer coefficients (**α_i**, **α_o**) must be known - or the values from the DIN standard must be used :*

$$\alpha_i = 7{,}69\ [W/m^2K]\ ;\ \alpha_a = 25\ [W/m^2K]$$

Wall with applied heat flux plate (wall'):



T_{Li}	=	*Air temperature, inside*	*[°C]*
T_{La}	=	*Air temperature, outside*	*[°C]*
T_{Wi}	=	*Wall temperature, inside surface*	*[°C]*
T_{Wa}	=	*Wall temperature, outside surface*	*[°C]*
q	=	*Heat flow density*	*[W/m²]*
R	=	*Thermal conductance resistance of the wall layer(s)*	*[m²K/W]*
R_i	=	*Thermal surface transfer resistance on the inside of the structural element*	*[m²K/W]*
R_a	=	*Thermal surface transfer resistance on the inside of the structural element*	*[m²K/W]*
α_i	=	*Thermal surface transfer coefficient, inside*	*[W/m²K]*
α_a	=	*Thermal surface transfer coefficient, outside*	*[W/m²K]*
λ	=	*Thermal conductivity of the wall layer(s)*	*[W/m K]*
s	=	*Thickness of the wall layer(s)*	*[m]*

R´	=	*Thermal conductance resistance of the heat flux plate*	*[m²K/W]*
q´	=	*Heat flow density of the heat flux plate*	*[W/m²]*
λ´	=	*Thermal conductivity of the heat flux plate*	*[W/m K]*
α_i´	=	*Thermal surface transfer coefficient of the heat flux plate, inside*	*[W/m²K]*
s´	=	*Thickness of the heat flux plate*	*[m]*

3.2.6 Procedure for measuring the U value

The thermal transmittance coefficient (U value) is an important rating in civil engineering and the construction industry where it is used to define a building's heat transmission losses through its various structural elements.
Heat transmission loss is the term used to describe the energy-saving qualities of a building's shell (i.e. the thermal insulation of its roof, outside walls, windows, and floors). In Germany each new residential structure is subject to a permissible maximum U value; this value is calculated as a function of the building's external surface area and internal volume - according to the most recently amended version of the Germany's energy-saving legislation (EnEV).
In view of the time shift between the measured heat flow density and the acquired temperature differences the measuring operation should only be performed in the following circumstances:

1. The temperature difference between interior and exterior ambient air must be sufficiently large. (Recommendation for normal insulation $\Delta T > 10K$; Recommendation for substantial insulation $\Delta T > 20K$)
2. Any fluctuations in these temperatures (e.g. day / night) should, throughout the measuring period, be as small as possible.
3. The measured values must be acquired and recorded on-site over a sufficiently long period (e.g. two or even several days) and then calculated on the basis of average values.
4. The measuring operation should only be performed when the temperature inside the building is steady (recommendation, approx. 20 °C).
5. The influence of the factors listed in Section 3.2.1, e.g. direct sunlight, moisture, etc., must be kept to a minimum (e.g. measuring at night, measuring in dry weather and on dry working surfaces)

3.2.7 Standardization

The method for calculating the thermal transmittance coefficient (U) is defined internationally in standard ISO 6946.
However, there is no standardized method for measuring the variables needed to perform this calculation. Practical measuring operations are performed on the basis of the formulae listed in DIN 4108 "thermal insulation in buildings". The measuring principle described in Section 3.2.5 is generally based on - but not exactly specified by - DIN 4108.

3

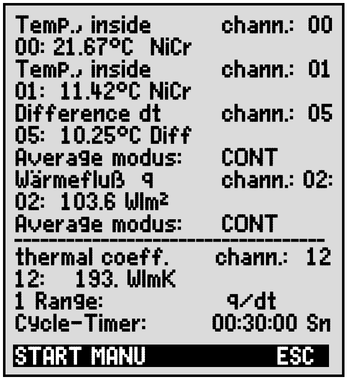
3.2.8 Performing thermal coefficient measurements using ALMEMO® measuring technology

For the practically minded

High thermal transmittance is obtained by ensuring a high thermal conductance resistance and a low thermal conductivity.
The higher the thermal transmittance coefficient - the larger the heat losses through the walls will be.
The higher the thermal transmittance resistance - the better the thermal insulation will be.

3.2.8.1 Arranging and programming the sensors, calculations performed in the ALMEMO® device

ALMEMO® devices 2690-8 and 2890-9 provide a wizard menu with which, depending on how the temperature sensor is used, a thermal coefficient (see Section 3.2.5) can be calculated from a long-term measuring series (device instructions, keyword “thermal coefficient”).



If both the heat flow density and the interior and exterior air temperatures are acquired, the value calculated in the device is the thermal transmittance coefficient (U value).
Example using the ALMEMO 2890-9 :
To determine the thermal coefficient $\overline{q}/(T1-T0)$ the two temperature sensors are connected as required to channels M0 and M1 and the heat flux plate to M2. The temperature difference T(M1)-T(M0) is obtained automatically on channel M5. For this measuring operation the following programming steps are needed:

Averaging mode on M9: **CONT**
Averaging mode on M2: **CONT**
Range on M12: **q/dt**
Enter the cycle by means of: **Cycle timer**
Start measuring by pressing: **<START>**
Stop measuring by pressing: **<STOP>**

3.2.8.2 Arranging and programming the sensors in the ALMEMO® device, calculations performed in AMR-WIN-CONTROL

The AMR-WIN-CONTROL software uses the measured values recorded with the ALMEMO® device to calculate the U value; it runs a U value wizard (see Catalog 06.10, 14.03) with menu guidance through the calculations and a graphical display of the U value.
Using this method there must be no averaging mode assigned to the sensors; this is because averaging and calculation are performed by the software.
The sensors measuring the heat flow density and the interior and exterior air temperatures can be freely assigned to any channels.
The correct assignment of the sensors is requested in the U value wizard.
Any V5 or V6 ALMEMO® device, ALMEMO 2590, 2690, 2890, 8590, 8690, 5690 with an internal or external memory can be used to perform these measuring and recording operations.
The U value wizard can also be used, depending on the assignment of the temperature sensors (air temperature or surface temperature), to calculate another thermal coefficient (for definition see Section 3.2.5) but this is not the U value.

3

3.2.8.3 Setup for measuring the U value on site

The heat flux plate should preferably be fitted on the inside wall. The bottom of the heat flux plate should be fitted as homogeneously as possible with the measuring point, e.g. by:

- sticking with double-sided PVC or fabric tape.
- Paper film should not be used because this might make the heat flux plate difficult to remove later.
- Applying heat-conducting paste to the bottom of the heat flux plate and fixing it in position with adhesive tape or mechanical fixture elements at the edge of the plate.
- Closeness to radiators or bay windows should be avoided.

Bare, thermo-wire sensors of different length are suitable as temperature sensors, type FT 390-0, welded to the tip.

For measuring the air temperature inside (T_{Li}) the measuring tip should be fitted at a distance of at least 10 cm above the heat flux plate and protruding approx. 10 cm into the room (appropriately bent).
For measuring the air temperature outside (T_{Lo}) the measuring tip should be led through a suitable bushing in the wall or window, fitted to the exterior wall, and protrude, similarly, approx. 10 cm from the exterior wall.

3.2.8.4 Setup for measuring other thermal coefficients on site

To obtain other thermal coefficients (see Section 3.2.5) the wall surface temperatures inside and outside must be measured.
Bare, thermo-wire sensors of different length are suitable as temperature sensors, type FT 390-0, welded to the tip.
For measuring the wall surface temperature inside (T_{Wi}) the measuring tip should be fitted by means of suitable adhesive tape directly next to the heat flux plate.
For measuring the wall surface temperature outside (T_{Wo}) the measuring tip should be led through a suitable bushing in the wall or window, fitted to the exterior wall by means of suitable adhesive tape.

☞ ***To minimize adverse environmental effects the temperature sensors can be physically protected on the outside by means of a metal sheet (against direct sunlight and moisture)***

For an overview of these measuring systems please refer to our 2009 Catalog, page 14.03.