In this case, the combined convection and radiation heat transfer coefficient of inner and outer surfaces will be included in the experimental value of $U_{\text{in-situ}}$ as they reflect the current indoor and outdoor conditions and could differ from values used in the theoretical approach (see Chap. 3). Meanwhile, if the surface temperatures of inner and outer surfaces are measured instead, the combined convection and radiation resistance ($R_{si}$ and $R_{se}$) must be added as theoretical values:

$$U_{\text{in-situ}} = \frac{1}{R_{\text{tot}}} = \frac{q}{(\theta_i - \theta_e)} \quad (W/m^2K)$$

where:
- $q$ is the specific heat flux ($W/m^2$)
- $\theta_i$ is the indoor air temperature ($^\circ$C)
- $\theta_e$ is the outdoor air temperature ($^\circ$C)
- $R_{\text{tot}}$ is the total heat transfer resistance of the building structure ($m^2K/W$)

$$U_{\text{in-situ}} = \frac{1}{R_{\text{tot}}} = \frac{1}{\left(\frac{1}{R_{si}} + \frac{1}{(\theta_i - \theta_e) + R_{se}}\right)} \quad (W/m^2K)$$

where:
- $R_{si}$ is the internal surface thermal resistance which combines convection and radiation resistance at the interior surface ($m^2K/W$)
- $R_{se}$ is the external surface thermal resistance which combines convection and radiation resistance at the exterior surface ($m^2K/W$)
Heat transfer in a building envelope is always unsteady because the temperature of outdoor air is time dependent, the surfaces of building elements absorb solar radiation, and the wind’s speed and direction are changing during measurement period. Even indoor temperature is not constant because of solar and internal heat gains. To compensate for heat accumulation in building construction, it first must be defined if the building structure should be treated as lightweight or heavyweight. This is done regarding to thermal capacitance $C$ of the structure, which is defined by equation (Fig. 4.5):

$$C_{k} = \sum_{i=1}^{n} d_i \cdot \rho_i \cdot c_i \quad \text{(J/m}^2\text{K)}$$

Lightweight structures are considered to have thermal capacitances lower than 20,000 J/m$^2$K. Such structures include window glazing or thinner thermal insulation panels. In the case of lightweight building components, it is assumed that the effect of accumulated heat in the building structure is negligible. Consequently, the thermal transmittance $U_{\text{in-situ}}$ is determined as an average value calculated by measured specific heat flux and temperature during measurement intervals, which are limited to night-time only, starting one hour after sunset and finishing at time of sunrise on the following day. The experiment is completed when the $U_{\text{in-situ}}$ values in the three consecutive days do not differ by more than $\pm 5\%$.
**Case study** Example of in-situ determination of $U_{g,\text{in situ}}$ value of double glazing. A heat flux meter was installed in the middle ($q_1$) and on the bottom of the glazing ($q_2$) (see position of heat flux meters in Fig. 4.6). Data on the graph show thermal transmittance $U$ calculated from night-time measurement data. It can be seen that because of higher air velocity in the case of mechanically ventilated space, the surface resistance is lower in comparison to non-ventilated space, resulting in the higher thermal transmittance of the glazing.

Only three consecutive nights were needed to fulfil the criteria of the repeatability of daily (night-time average) $U_{g,\text{in situ}}$ values. The in-situ determined value of glazing was $U_{g,\text{in situ}} = 1.28 \text{ W/m}^2\text{K}$ in the middle and $U_{g,\text{in situ}} = 1.21 \text{ W/m}^2\text{K}$ at the bottom of the glazing. When the ventilation system was operating, air velocity was higher and internal surface thermal resistance $R_{si}$ difference was lower and dependant on location. When natural convection is present at the internal surface of the glazing, resistance was lower and unified across glazing, resulting in $U_{1,\text{in situ}}$ equal to $U_{2,\text{in situ}}$. As the producer of the glazing states that the $U$-value is $1.2 \pm 0.1 \text{ W/m}^2\text{K}$, the manufacture’s data was confirmed.

In the case of the heavyweight building components, measurement is carried out in the same way, but throughout the day. Thermal transmittance is then determined based on the average values of specific heat flux and the difference between indoor and outdoor air temperatures. The duration of the measurement can be shortened with the use of the thermal mass correction factors ($F_i$ determine according to heat accumulation of inner part of construction and $F_e$ determine according to heat accumulation of outer part of building construction), where the stored heat in a building component is taken into account with the correction of the measured specific heat flux. The following equation is used for the determination of the thermal transmittance $U_{\text{in-situ}}$ of heavy-weight structures:
According to the standard ISO 9869,\(^2\) measurements must take place for at least 4 days. The experiment is completed when the calculated U-value does not differ by more than \(\pm 5\%\), referring to the U-value measured 24–48 h previously.

**Case Study** Example of in-situ determination of \(U_{\text{in-situ}}\) value of brick wall. Thermal capacitance \(C\) of the structure is equal to 1,224,000 J/m\(^2\)K and the procedure intended for heavyweight structures must be used. From the figure, it can be seen that duration of experiment could be (much) shorter if thermal mass correction factor is used (Fig. 4.7).

Theoretical (calculated) thermal transmittance \(U\) of the wall is equal to 0.91 W/m\(^2\)K, and measured thermal transmittance of the wall is \(U_{\text{in-situ}} = 0.95 \pm 0.08\) W/m\(^2\)K. Interval \((\pm 0.08\) W/m\(^2\)K\) was determined with error analysis, taking into account the accuracy of each sensor.

![Fig. 4.7 Position of heat flux meter (left); calculated of thermal transmittance at area M1 (right)](image_url)

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4.3 In-Situ Determination of Glazing Total Solar Energy Transmittance \( g \)

Total solar energy transmittance \( g \) is a property of the glazing that defines solar gains. In addition to laboratory testing and numerical modelling based on optical properties of glass panes and gas filling, it can be evaluated in situ, implementing the following procedure:

- heat transmittance of glazing \( U_g \) must be determined first by measuring specific heat flux and indoor and outdoor air temperature differences, as described in Sect. 4.2.
- virtual surface temperature of indoor glass surface \( q_{si,vir} \) must be calculated, assuming that glazing is not exposed to solar radiation by equation:

\[
\theta_{si,vir} = \theta_i - \frac{U_g \cdot (\theta_i - \theta_e)}{R_{si}} \quad (\degree C)
\]

- at in situ conditions and when a window is exposed to solar radiation, the actual surface temperature of indoor glass \( \theta_{si} \) is measured (usually at such conditions \( \theta_{si} \) is greater than \( \theta_{si,vir} \)) and heat flux that is transferred by convection and radiation from indoor surfaces of the glazing to the indoor air is defined by equation (Fig. 4.8):

![Fig. 4.8](image-url)
using data of measured global (direct and diffuse) solar irradiation on the plane of the outside window glazing and transferred solar irradiation into the interior, the total solar transmittance of the glazing is defined by equation (Fig. 4.9):

\[
q_{i,c+r} = \alpha_{si} \cdot (\theta_{si} - \theta_{si,vir}) \quad (W/m^2)
\]

- using data of measured global (direct and diffuse) solar irradiation on the plane of the outside window glazing and transferred solar irradiation into the interior, the total solar transmittance of the glazing is defined by equation (Fig. 4.9):

\[
g = \frac{G_{glob,i} + q_{i,c+r}}{G_{glob,e}}
\]

4.4 In-Situ Determination of the Building Envelope Thermal Insulation with Thermography

Thermography is a method of remote sensing of the heat flux emitted by the surfaces using a thermal (or infra-red (IR)) camera. Each body with a surface temperature above absolute zero (0 K) emits from its surface heat flux in the form of electromagnetic radiation and is called a thermal emitter. A black body is a
A thermal emitter that emits at a specific surface temperature $T$ (measured in K) maximum (possible) heat flow. The intensity of the emitted heat flow and the wavelength of emitted radiation heat flow depends on the absolute temperature of the emitter’s surface. At the same time, the increasing of the temperature of thermal emitter causes the emitter to emit larger heat flux, and the wavelength of emitted radiation become shorter and shorter. The range of wavelengths of the thermal radiation and the intensity of the emitted radiation at a certain wavelength is expressed by Planck’s equation for blackbody radiation. This mathematical expression is presented in graphical form in Fig. 4.10 as monochromatic spectral emissive power.

Total emitted radiation heat flux is defined by the integration of monochromatic radiation heat flux over all wavelengths. This integral can be expressed in simple form as the Stefan-Boltzmann law:

**Fig. 4.10** According to the Plank’s law, building structures (treated as blackbodies here) have such a temperature that they emit maximal spectral thermal radiation at wavelengths between 8 and 14 $\mu$m. For these wavelengths, the Earth atmosphere is transparent and, therefore, do not disturb remote sensing with thermography. For high-temperature applications, such as furnace inspections, the spectral response of IR sensors in thermal cameras should be in the range of 3–5 $\mu$m.
In reality, no emitter is perfect (=black body), and emitted radiation heat flux is lower. The ratio between the actual emitted heat flux and heat flux emitted by a black body at the same absolute temperature is called emissivity; for real emitters, the total emitted heat flux is equal to:

\[
\dot{Q} = \sigma \cdot \varepsilon \cdot T^4 \cdot A \quad (W)
\]

Thermal cameras have integrated calculation routines that convert the measured heat flux to a more representative quantity, the surface temperature, by using the Stefan-Boltzmann law. Before performing thermography measurements, one must adjust the emissivity of observed areas. As most building materials have high emissivity (\(\varepsilon \approx 0.9\)) and emit radiation as diffuse emitters, thermal imaging is a widely used technique for the evaluation of buildings; nevertheless, exact thermal properties, such as the determination of heat transfer coefficient \(U\) or thermal bridge heat transmittance \(\psi, \chi\), cannot be evaluated directly. Conditions for the implementation of thermography in the thermal properties evaluation of buildings are defined in standard EN ISO 6781-3.³ The most important requirements are:

- at least 24 h before thermography, the outdoor air temperature should not vary by more than \(\pm 10 \, ^\circ C\);
- at least 24 h prior to and during thermography, the temperature difference between indoor and outdoor air temperature should at least \(3/U\) \((^\circ C)\) (where \(U\) is thermal transmittance of the building envelope) and in any case not less than \(5 \, ^\circ C\);
- at least 12 h before thermography, the building envelope must not receive direct solar radiation
- during thermography, the indoor air temperature shall not vary by more than \(\pm 2 \, ^\circ C\) and outdoor temperature by more than \(\pm 5 \, ^\circ C\);
- during thermography, the sky must be cloudy.

For the interpretation of thermal images, it is important that during the heating season building structures with lower thermal transmittance \(U\) have higher inner and lower outer surface temperatures, as shown on Fig. 4.11. Some examples are presented in a case study below (Fig. 4.12).

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4.5 In-Situ Determination of Building Airtightness

The air tightness of buildings is essential to reducing the air infiltration leaky joints in the building envelope. As heat losses increase, cold winter air can cause cooling of the building structure below the dew point which can lead to increased water content in the building structure; air infiltration can cause unpleasant draught and thus thermal discomfort. Consequently, requirements regarding the airtightness of the building are defined in EU regulations on energy efficiency of the buildings.

Airtightness of the building can be tested in two ways:

- by measuring the time-dependent decrease of tracer gas concentration after a specific level of tracer gas was established in the room (building) at the start of the test; the less the building is tight, the quicker the tracer gas concentration reaches the outdoor level;
- by measuring the flow rate of air the passing building envelope at an elevated (positive and negative) pressure difference between the building interior and ambient environment created by a fan; a higher pressure difference is necessary for more accurate measurement of air flow rate and to prevent the impact of natural ventilation; for airtight testing of buildings, this method is required.

As mentioned, the difference in the air pressure is generated by a fan, which is installed with a tight sheet in an opening in the building envelope, most often on the door opening, as shown in Fig. 4.13. This is why the test is named in engineering practice as “the blower door test”.

The blower door test can be performed by two methods: by Method A (EN ISO 9972\textsuperscript{4}) when the building is in full operation regime or by Method B at which all openings are sealed (for example, a channel for supply and exhaust air in the system of mechanical ventilation) and only the airtightness of building envelope is tested.

Case study: Interpretation of thermal images of a building envelope of a non-thermal insulated building taken during the heating season.

Warm upper and cold lower window frame areas indicate air leakage. As some windows are open, this indicates inadequate ventilation of the rooms.

High surface temperatures indicate that the brick wall is not thermally insulated; even higher temperature above the ground indicates that wall is moist.

Heat bridges on the columns and floor slab can be observed here.

Using thermography, the quality of thermal insulation of heat generators, pipelines and storage tanks can also be checked.

Fig. 4.12 Thermal images of case study building envelope and building service system elements