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Thermal insulation of building elements — In-situ measurement of thermal resistance and thermal transmittance —

Part 3: Probe insertion method

Isolation thermique des éléments de construction — Mesurage in situ de la résistance thermique et du coefficient de transmission thermique —

Partie 3: Méthode par insertion d'une sonde

Reference number
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Foreword

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This document was prepared by Technical Committee ISO/TC 163, *Thermal performance and energy use in the built environment*, Subcommittee SC 1, *Test and measurement methods*.

A list of all parts in the ISO 9869 series can be found on the ISO website.

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Introduction

The ISO 9869 series describes the in-situ measurement of the thermal transmission properties of plane building components, primarily consisting of opaque layers perpendicular to the heat flow and having no significant lateral heat flow. The thermal transmittance of a building element (U-value) is defined in ISO 7345 as the heat flux per unit area and unit temperature difference in the steady state condition. Since steady state conditions are never encountered on a site in practice, such a simple measurement is not possible. Although various statistical methods have been introduced to address this problem, one of the simplest is the use of the mean values over a sufficiently long period of time. The required time for observation for reliable measurements depends on the thermal properties of the building components and the nature of the temperature difference between the surroundings on each of the sides thereof.

ISO 9869-1 describes the method used to estimate the thermal steady state properties of a building element from heat flow meter (HFM) measurements through plane building components. Annex B describes the statistical methods of the simple mean and the sophisticated method of dynamic analysis for steady state properties. This document describes a screening test of the insulation condition and thermal resistance of existing building elements by visual observation with a borescope and by measurement of the temperature gradient and heat flow with a temperature sensing rod and HFM. Although the method used in this document is not a non-destructive inspection method, the diameter of the borehole drilled through the building element is approximately less than 2 mm. The method described in this document is intended for use as a practical diagnostic procedure of the thermal transmission properties of plane building components with light heat capacity such as those in frame structure dwelling.

The thermal performance of a part of the building element is evaluated by obtaining the temperature gradient through the building element and the heat flow rate. The thermal transmittance (thermal resistance) of the insulation layer of the building components for the steady state condition can be obtained by using the averages of the observed values over a certain period of time.

Thermal insulation of building elements — In-situ measurement of thermal resistance and thermal transmittance —

Part 3: Probe insertion method

1 Scope

This document describes a method for measuring the insulation performance of building elements, e.g. exterior walls, floors, ceilings (hereinafter referred to collectively as "walls"). This is done by using the probe insertion method, which gives the temperature distribution in the wall with a temperature sensor in a small diameter borehole in the wall.

The measurement method is divided into a quantitative method, which measures the thermal resistance with a heat flow measurement, and a qualitative method without heat flow measurement.

This document describes a screening test that is used for preliminary and practical diagnosis.

The method is applicable to plane building components with a light heat capacity, such as those in frame structure dwellings. The measured results give the insulation performance at the local measurement points rather than that of the whole panel including thermal bridges such as studs.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 7345, *Thermal performance of buildings and building components — Physical quantities and definitions*

ISO 9869-1, *Thermal insulation — Building elements — In-situ measurement of thermal resistance and thermal transmittance — Part 1: Heat flow meter method*

IEC 60584-1, *Thermocouples–Part 1: EMF specifications and tolerances*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 7345 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
borescope
optical device consisting of a rigid or flexible tube with an eyepiece on one end and an objective lens on the other end, linked together by a relay optical system in between, which is surrounded by optical fibres used for illumination of the remote object

Note 1 to entry: Rigid or flexible borescopes may be fitted with an imaging or video device.

4 Symbols and units

Table 1 — Symbols and units

Symbol	Quantity	Units
k	thermal conductivity	W/(mK)
x	depth from the inner surface of the building element	m
L	thickness of the insulation layer	m
θ	temperature	°C
Q	heat flow rate	W/m^2
R	thermal resistance	(m^{2}K)/W

5 Principle

5.1 General

One of the two following methods shall be applied.

5.2 Method without heat flow measurement

A borehole with an approximately 1 mm diameter is drilled through the interior solid lining material (e.g. Gypsum board). A borescope is inserted and the presence or absence of an insulation layer is confirmed and the type and thickness of the insulation layer can also be observed. After visual inspection, a rod-shaped temperature sensor is inserted, which measures the temperature distribution along the depth of the borehole. The internal and external surface temperatures of the wall are also measured. Based on these measurements, an illustration of the cross-sectional temperature distribution at that location across the wall is made. Although the section temperature distribution obtained in the borehole is not an exact representation of the temperature distribution of the insulation layer, the two-side temperature of the insulation layer can be measured with a certain degree of accuracy. The degree of accuracy depends on the conductance of the rod-shaped temperature sensor, the insulation layer and any other relevant parts. The obtained temperature distribution shall be used as a basis for determining the quality of the insulation layer as follows:

a) The thermal performance of the insulation material is evaluated from the ratio of the two-side temperature difference of the insulation layer and that of the internal and external temperatures of the wall (the observed building element).

b) The temperature distribution curve prepared based on the measurement results is compared with the expected section temperature distribution assuming that the insulation material is functioning properly. The discrepancy between the two temperature distribution curves provides diagnostic criteria for determining whether, for example, the insulation layer is properly installed or not, or whether the insulation layer has already experienced aging degradation or not.

5.3 Method with heat flow measurement

In addition to the method described in 5.2, the heat flow is measured at the indoor side surface of the wall (building element). The thermal resistance of the insulation layer of the wall or the whole wall is obtained as the quotient of the two-side temperature difference of the measured insulation layer divided by the heat flow rate.

6 Apparatus

6.1 Temperature measuring devices

6.1.1 Type of sensors and accuracy

Thermocouples, resistance thermometers, or thermistors may be used to measure the temperatures inside the wall, on the surface, and in the air. Thermocouples shall be type T and shall satisfy the tolerance of class 1 described in IEC 60584-1. For resistance thermometers or thermistors, the error of temperature measurement converted from the resistance tolerance shall be less than 0,5 °C.

6.1.2 Sensor for measuring temperature distribution in walls

The sensor shall have the following specifications with a rod-like thermometer:

a) The temperature sensor shall be coated.

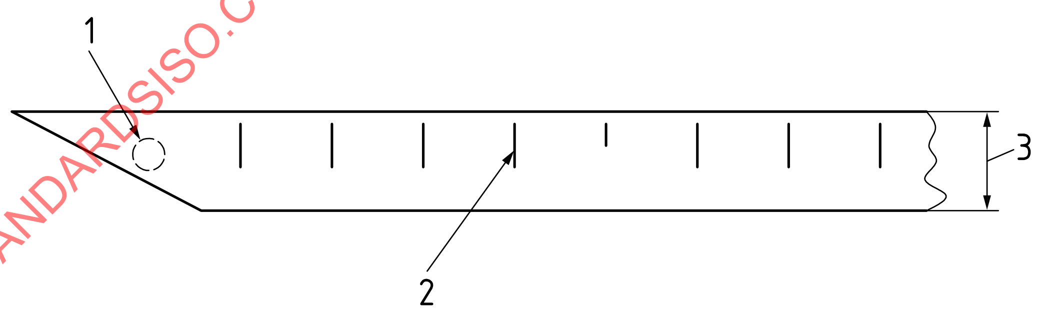
b) The tip shall be processed in a needle-like shape, as shown in Figure 1, in order to penetrate the insulation material without deforming the installed insulation layer. This type of sensor is already manufactured and is commercially available for food processing applications. A temperature sensor with a hard tube shell, as shown in Figure 2, can also be used. The tip of the tube shell shall have a needle shape and the tube shell shall be hard enough to penetrate the insulation layer.

c) The diameter of the sensor rod, including the coating, shall be not more than 1,0 mm. The outer diameter of the tube shell, if any, shall not exceed 1,3 mm.

d) The sensor rod shall have a scale indicating the insertion depth of the temperature sensing portion.

e) The sensor rod may have one or more than one temperature sensing portion. In sensor rods with multiple sensing portions, the sensing portions shall be arranged at the same interval (not to exceed 15 mm) along the rod, as shown in Figure 3. Use of a sensor rod with more than one sensing portion makes it possible to measure the temperature distribution along the borehole without traversing the sensor.

f) The thermal bridge effect of the sensor-rod shall be small enough that the value of $N_{c,nom}$ obtained by the calibration method shown in Annex A (normative) is less than 0,5.



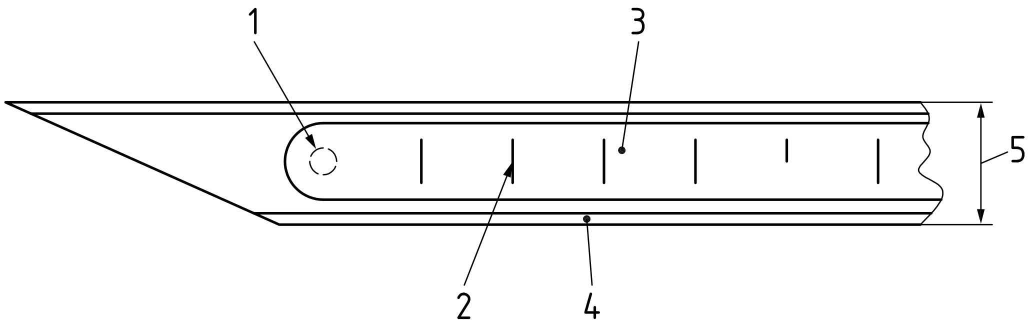
Key

1 temperature sensing portion

2 scale

3 diameter of sensor rod

Figure 1 — Temperature sensor with a needle-like shape (tip part)



Key

1 temperature sensing portion

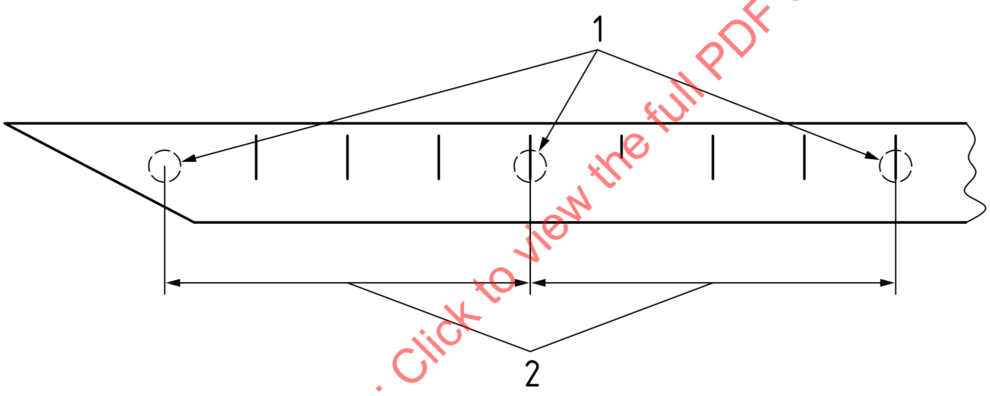
2 scale

3 temperature sensor

4 tube shell

5 outer diameter of tube shell

Figure 2 — Temperature sensor with a hard tube shell (tip part)



Key

1 temperature sensing portions

2 interval of sensing portions

Figure 3 — Temperature sensor having multiple sensing portions (with a needle-like shape, tip part)

6.1.3 Sensors for measuring surface and air temperatures

The sensors for measuring the surface and air temperatures shall be in accordance with ISO 9869-1, except that thermistor sensors can also be used.

6.2 Borescope

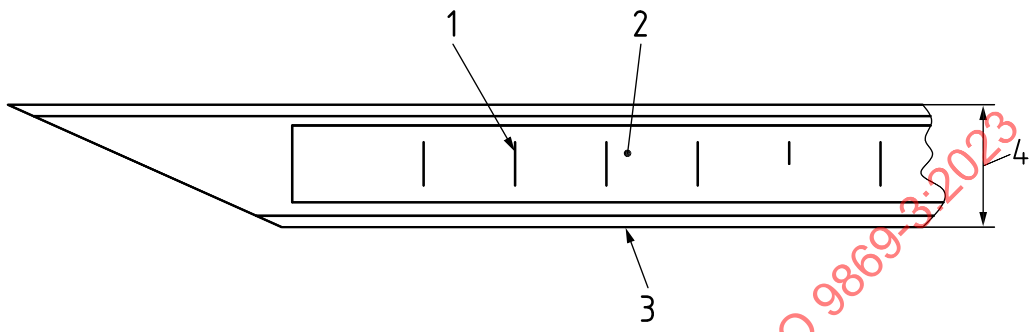
A borescope is used to visually check the condition of insulation installation and the thickness of the insulation layer in the wall (building element).

a) The borescope shall have an illumination device. The viewing angle shall be sufficiently wide and the visual resolution shall be sufficiently fine to determine reliably whether insulation material is present in the wall (building element) or not;

b) The borescope itself shall have a needle tip shape that can penetrate the insulation layer. A borescope with a hard tube shell can be also used, as shown in Figure 4. The tip of the tube shell shall have a needle shape and the tube shell shall be hard enough to penetrate the insulation layer;

c) The outer periphery of the borescope shall have a scale indicating the insertion depth;

d) The borescope shall have a diameter of not more than 1,5 mm, including the tube shell, and a length greater than the thickness of the targeted wall (building element).



Key

1 scale

2 borescope

3 tube shell

4 diameter of borescope including tube shell

Figure 4 — Borescope with a hard tube shell (tip part)

6.3 Heat flow meter (HFM)

An HFM is required when measuring the thermal resistance of the insulation layer and shall be the same as that described in ISO 9869-1.

7 Locations of the measured area and sensor installation

Figure 5 shows the schematic of the measured area and the measurement apparatus. The measured area of the targeted wall (building element) shall be sufficiently larger than 400 × 400 mm and shall face indoors. The measured area shall not include the frame section or other elements which cause heat bridges. The measured area should be chosen in advance based on the drawings of the building or thermal images acquired with an infrared camera.

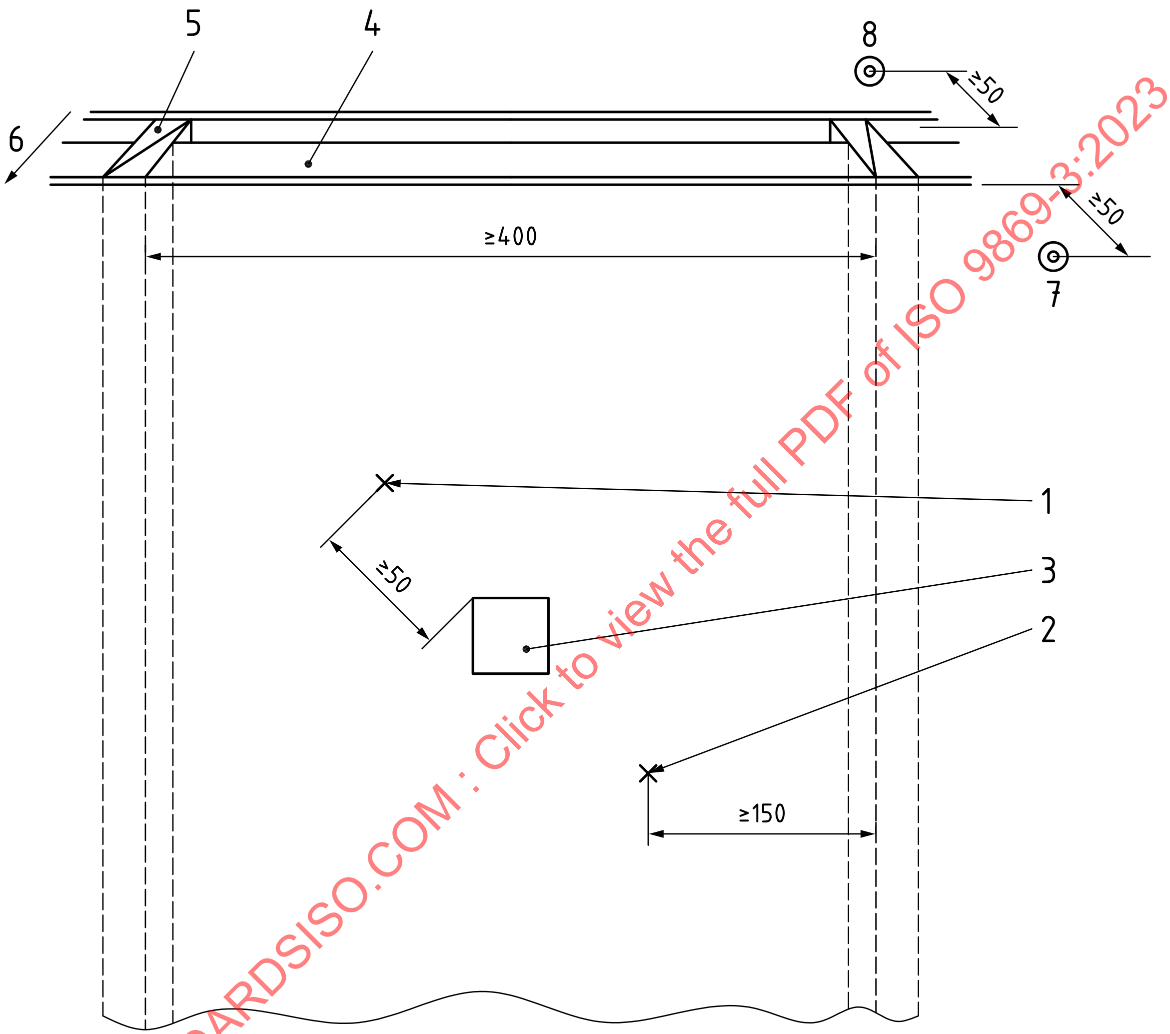
The temperature sensor(s) on the internal and, if possible, on the external surface of the wall is (are) installed in the vicinity of the centre of the measured area. When heat flow measurements are made, an HFM shall also be installed in the vicinity of the centre on the interior surface of the wall. In addition to the surface temperature measurement, temperature sensors shall also be installed in the room and on the opposite side of the wall to measure the air temperature. If it is difficult to install a sensor on the opposite side of the wall, for example, when measuring a floor or ceiling, the sensor shall be installed outside the building in a well-ventilated area that is not affected by solar radiation.

The number of test positions for observing the interior of the wall with a borescope and measuring the temperature distribution inside the wall shall be more than one, and the thermal conditions of all test positions should be assumed to be the same. It is recommended that the test positions be separated as far as possible from each other within the measured area. The distance between the borehole and the HFM or the temperature sensor shall be not less than 50 mm. The distance between the frame structure and the HFM, temperature sensor and the borehole shall be not less than 150 mm. The temperature sensor incorporated in the HFM can also be used. Only one traverse with a temperature sensor or borescope is allowed for each bore hole, except in cases where the insulation material proves to be fibrous, in order to avoid air infiltration that can create an exchange between the cold and warm surfaces. For example, in the case of foam-based insulation, at least four boreholes need to be provided to obtain two measurement samples each from the borescope and the temperature sensor.

NOTE The size and homogeneity of the wall (building element) affects the number of measuring points and the uncertainty of the method.

Installation of the apparatus, other than as noted above, shall be in accordance with ISO 9869-1.

Dimensions in millimetres



Key

1 test position 1 (borehole)
2 test position 2 (borehole)
3 HFM, temperature sensor
4 insulation
5 stud
6 interior
7 room temperature
8 external temperature

Figure 5 — Schematic of the test positions and apparatus

8 Measurement conditions and period

8.1 General

Test positions where the external surface is exposed to solar radiation shall be avoided. The room temperature shall be controlled so that the temperature difference between the indoor and exterior wall surfaces is more than 10 °C. It is recommended to maintain a constant room temperature for at least 3 h before starting the temperature and heat flow measurements.

NOTE In order to estimate the required preheating time more accurately, it is helpful to calculate the time constant of heat flow response to a step change in room temperature based on the assumed cross-sectional configuration, using heat transfer simulation or other measures.

8.2 Method without heat flow measurement

The time and period of the test are not specified. However, the temperature distribution measured during a period of large outdoor temperature change can be unsteady and can be affected by the heat capacity of the wall.

8.3 Method with heat flow measurement

In order to reduce the influence of the thermal capacity of the wall, the test should be conducted at night when temperature change is small, or the test should be conducted over multiple periods of 24 h. The indoor air temperature variation should preferably be kept within 2 °C.

The electrical data from the HFM and temperature sensors shall be recorded continuously. The maximum recording interval shall be 10 min. It is recommended that each recording be the average value of several measurements sampled at shorter intervals, especially in the case of heat flow measurements, in order to minimize the effect of heat flow fluctuations.

9 Measurement procedure

9.1 General

In this document, the tested wall (building element) is described as a single panel structure, such as an insulation layer enclosed between two hard boards. However, the measurement method can also be applied to other component types of walls. This document assumes only that the tested wall (building element) consists of a hard layer where the boreholes are drilled and a soft layer where the borescope or temperature sensor rod can be inserted without drilling.

9.2 Method without heat flow measurement

a) A small drilled borehole is provided at the test position of the indoor finishing hard board of the wall (building element), such as a gypsum board or a wooden board. The borehole is used to insert the borescope or the temperature sensor rod for measuring the temperature distribution through the wall.

b) The borescope is inserted within the borehole so that the scope tip touches the hard board surface on the opposite side of the targeted wall, such as the outer side hard board surface of the wall. Therefore, the scale of the borescope can be used to measure the distance between the indoor finishing surface and the internal surface of the outer side board, which is referred to hereinafter as the wall depth. If the borescope is used together with a hard tube shell, the borescope shall be introduced into the shell, as shown in Figure 4, and then inserted together with the shell in one piece until it touches the outer side board. The shell is then removed while making sure that the depth of the borescope does not change.

NOTE If a sheet material is applied on the outer side of the insulation material, the tip of the borescope can penetrate or deform the sheet material, and the measured thickness of the insulation layer can be thicker than the actual value.

c) The borescope is slowly pulled back into the room, and when the outer edge of the insulation is observed, the pullback motion is stopped and the depth of the borescope insertion is read. This position is the exterior side surface of the insulation layer. Then the borescope is again slowly pulled back into the room until no insulation is observed, the pullback motion is stopped again, and the depth of the borescope insertion is read. The thickness of the insulation layer can be evaluated from these two depth position measurements. The depth of the airgap in the wall or the thickness of the hard board of the wall can also be measured in a similar manner.

d) The borescope is pulled out, and the temperature measurement sensor rod is inserted into the wall borehole instead. When using a temperature sensor rod with more than one sensing portion, the sensor rod position can be fixed, and then the temperature distribution can be measured. The measurement shall be done after the measured temperature variations become small enough to be assumed to be in the steady state condition. When using a temperature sensor rod with only one sensing portion, the temperature distribution is measured by pulling back the rod in equal length intervals (however, less than 15 mm). In this case, the temperature shall be measured at each depth in the steady state condition, after the measured temperature fluctuations become sufficiently small. If observation by the borescope does not confirm that the insulation is fibre-based, then separate holes shall be made for the temperature sensor and the borescope to avoid the effect of the inflow of air from inside and outside through the hole.

e) Together with the measurement of the temperature distribution inside the wall, the surface and air temperatures inside and outside the wall should also be measured.

f) Based on the measured temperatures at each position, a diagram illustrating the cross-sectional temperature distribution in the wall (building element) is prepared.

9.3 Method with heat flow measurement

a) The wall depth, insulation layer thickness, its position and the temperature distribution, including the surface, room and external temperature, shall be measured by the same procedure as described in 9.2.

b) The temperature sensor rod inserted in one of the test positions is fixed so that the tip sensing position is located at the exterior side surface of the insulation layer, as described in 9.2 c). If the tip sensing portion cannot be fixed at that position in cases where the entire space in the wall cavity is occupied by the insulation material, then the tip should be fixed at the 10 mm pullback position from the exterior side hard board surface, as in 9.2 b). In this case, the depth of the sensing portion shall be recorded.

c) If the measurement is planned for the period from night to dawn, the temperature and the heat flow rate shall be continuously measured until the tentatively evaluated thermal resistance from the surface of the indoor wall to the external surface of the insulation layer, as calculated by Formula (1), reaches the steady state. If the tentatively evaluated thermal resistance obtained with Formula (1) does not show a steady state value, the test shall be conducted over a period of multiples of 24 h.

$$R_t = \frac{\left|\bar{\theta}_{s,i} - \bar{\theta}_{s,o}\right|}{\bar{Q}} \qquad (1)$$

where

R_t is the tentatively evaluated thermal resistance from the surface of the indoor wall to the external surface of the insulation layer [(m^{2}K)/W];

$\bar{\theta}_{s,i}$ is the time averaged temperature at the internal surface of the wall, expressed in degrees Celsius (°C);

$\bar{\theta}_{s,o}$ is the time averaged temperature at the external surface of the insulation layer measured by the sensor probe [°C];

$\bar{Q}$ is the time averaged heat flow rate measured by the heat flow meter (HFM) [W/m^2].

The thermal resistance for reporting purposes is calculated according to Clause 10. When the variation of the calculated thermal resistance value R_t (the RMS value for the most recent 2 h of observation) becomes less than 10 % of the 2 h averaged value of thermal resistance R_t, it is assumed that the steady-state condition has been attained. Here, the values of $\bar{\theta}_{s,i}$, $\bar{\theta}_{s,o}$ and $\bar{Q}$ used in the calculation of thermal resistance R_t by Formula (1) should be the 10 min time-averaged values.

d) If the measurement is planned to extend over multiple periods of 24 h, the temperature and the heat flow rate shall be continuously measured over the whole observation period.

10 Calculations

10.1 Thickness of wall components

As noted in Clause 7, the measurement of the thickness of each layer by the borescope shall be performed at more than one test position. The thickness of each layer shall be reported by calculating the average value of the measurements at the different test positions.

10.2 Temperature distribution

As noted in Clause 7, temperature measurements at each depth by the sensor probe shall be conducted at more than one test position. The temperature at each depth shall be reported by calculating the average of the measured values at the different test positions. If the measurements are taken continuously in time, take the time average for each test position, and then take the average between the different test positions.

In addition, if the measurements are taken continuously in time, the surface and air temperatures inside and outside the wall shall be reported by time averaged values.

10.3 Thermal resistance

The thermal resistance from the internal surface of the wall to the external surface of the insulation layer is estimated from the measurement as Formula (2):

$$R = \frac{\left|\bar{\theta}_{s,i} - \hat{\theta}_{s,o}\right|}{\bar{Q}} \tag{2}$$

where $\hat{\theta}_{s,o}$ is the corrected time averaged temperature at the external surface of the insulation layer [°C].

The corrected time averaged temperature at the external surface of the insulation layer measured by the sensor probe is calculated by Formula (3):

$$\hat{\theta}_{s,o} = \frac{\bar{\theta}_{s,o} - \theta_d^* \times \bar{\theta}_{s,i}}{1 - \theta_d^*} \quad (3)$$

where

$\bar{\theta}_{s,o}$ is the time averaged temperature at the external surface of the insulation layer measured by the sensor probe [°C];

θ_d^* is the non-dimensional temperature deviation at the external surface of the insulation layer.

The non-dimensional temperature deviation at the external surface of the insulation layer is calculated by Formula (4):

$$\theta_d^* = -0{,}023 + 0{,}291\sqrt{N_c} \quad (4)$$

where

$$N_c = \left(\frac{L_{nom}}{L}\right)^2 \times \frac{\ln(2L/\phi_s)}{\ln(2L_{nom}/\phi_s)} \times N_{c,nom} \quad (5)$$

and

L_{nom} is the nominal thickness of insulation material (=0,05 m);

L is the average thickness of the insulation material measured by the borescope [m];

ϕ_s is the diameter of the sensor probe used [m];

$N_{c,nom}$ is the nominal N_c value of the sensor probe used, obtained by the procedure in Annex A [-].

NOTE Formula (3) is obtained by setting x^*=1 in Formula (A.1) and solving for $\theta_{s,o}$. Formula (4) approximates the relationship between the N_c value and the non-dimensional temperature deviation at a non-dimensional depth of 0,9 in Figure A.1. Formula (5) is obtained by inserting k_m=$k_{m,nom}$ in Formula (A.2) and solving for N_c.

11 Test report

The following items shall be described in the report of the test results.

a) data of the targeted building (location, structure, floor area, measurement position, direction of plane outline);

b) test position map (view from the room, including, e.g. measurement points, openings, studs);

c) test day and time;

d) elapsed time between starting the adjustment of the room temperature and starting the test;

e) ambient conditions (e.g. sunshine, wind, in case the test portion is an external wall or roof);

f) specification of the method as either with or without heat flow measurement;

g) specifications of the HFM, borescope and temperature sensors used in measurement of the surface and air temperatures inside and outside the wall;

h) specification of the temperature sensor for internal temperature measurement of the wall (e.g. type, coating, diameter, time constant, value of $N_{c,nom}$ and uncertainty evaluated according to A.5);

i) presence or absence of the insulation layer checked by the borescope, the thickness of each wall component checked by the borescope and the results of visual inspection of the insulation layer (e.g. aging degradation);

j) images of the insulation material acquired with the borescope;

k) cross-sectional temperature distribution through the test position, including the surface and air temperatures inside and outside the wall;

l) thermal resistance from the internal surface of the wall to the external surface of the insulation layer, the results of the uncertainty analysis according to Annex B and the depth of the sensing portion of the temperature sensor rod from the internal surface of the wall for evaluating thermal resistance;

j) any deviations from the procedure and any unusual features observed.

Annex A
(normative)

Evaluation of the effect of thermal bridges on the sensor for measuring the temperature distribution in the wall

A.1 General

This Annex describes a method for evaluating the effect of thermal bridges on a sensor rod buried in a material with small thermal conductivity.

A.2 Principle

A temperature difference is provided on the two sides of a uniform insulation material, and the temperature inside the insulation material is measured with the temperature sensor rod to be tested inserted. The effect of thermal bridges can be estimated from the discrepancy between the measured distribution obtained with the tested sensor rod and the estimated temperature distribution, which is assumed to be linear in the uniform insulation material.[1]

A.3 Apparatus

The specifications of the apparatus are the following.

A.3.1 Sensor rod for measuring temperature distribution in walls

The diameter of the sensor rod tested shall be less than 1 mm. The sensor which is to be tested shall be calibrated in advance, together with its data-logging system, using a standard thermometer in the operating temperature range.

A.3.2 Insulation material

The insulation material shall be a foam-based plate-shaped sample of known thickness and thermal conductivity. The thickness of the insulation material shall be in the range from 50 mm to 100 mm.

A.3.3 Temperature sensor for measuring surface temperature

T-type thermocouples as specified in IEC 60584-1 shall be used to measure the insulation surface temperature. The wire shall have a diameter of less than 0,2 mm and shall be calibrated together with the data-logging system in the operating temperature range.

A.3.4 Wind speed meter

The wind speed near the surface of the insulation material shall be measured.

A.4 Method

The measurement method is the following.

a) The insulation material is fixed with an appropriate frame. The temperature difference between the two surfaces of the insulation material shall be maintained at more than 10 K and kept in a steady state. A constant temperature chamber box installed in a constant temperature-controlled room or an artificial climate chamber room divided into two chambers with different temperatures may be used.

b) On one side of the insulating material (hereinafter referred to as the "insertion side"), the wind speed is measured at a position 30 mm from the surface, using care with regard to the directivity of the wind speed sensor. The average measured wind speed shall not exceed 0,1 m/s.

c) The sensor rod for measuring the temperature distribution in the insulation material is inserted from the insertion side of the insulation material and is fixed so that the temperature sensing portion is embedded in the insulation material. The distance between the temperature sensing portion and the insertion side surface at this time is set to be 4/5 of the thickness of the insulation material. If it is difficult to insert the sensor rod into the insulation material for reasons such as the insufficient strength of the temperature sensor or the like, it is necessary to make a hole having a diameter no larger than that of the sensor rod in the hard material to the corresponding depth in advance. Further, when using a sensor rod having more than one temperature sensing portion, the temperature sensing portion closest to the tip is to be positioned at the corresponding depth.

d) At the depth described in c) above, the temperature is measured after the time variation of the temperature becomes sufficiently small. The temperature sensor is then pulled back to the insertion side so that the distance between the temperature sensing portion and the insertion side surface is 3/5 of the thickness of the heat insulation material. By repeating this operation, temperature measurements are performed at depths of 4/5, 3/5, 2/5 of the thickness of the insulation material.

e) Based on the measured temperature at each depth, the non-dimensional temperature deviation is calculated using Formula (A.1):

$$\theta_{\mathrm{d},k}^{*} = \frac{\theta_k - \theta_{\mathrm{s,o}}}{\theta_{\mathrm{s,i}} - \theta_{\mathrm{s,o}}} - \left(1 - x_k^{*}\right) \tag{A.1}$$

where

$\theta_{\mathrm{d},k}^{*}$ is the non-dimensional temperature deviation at each depth [-];

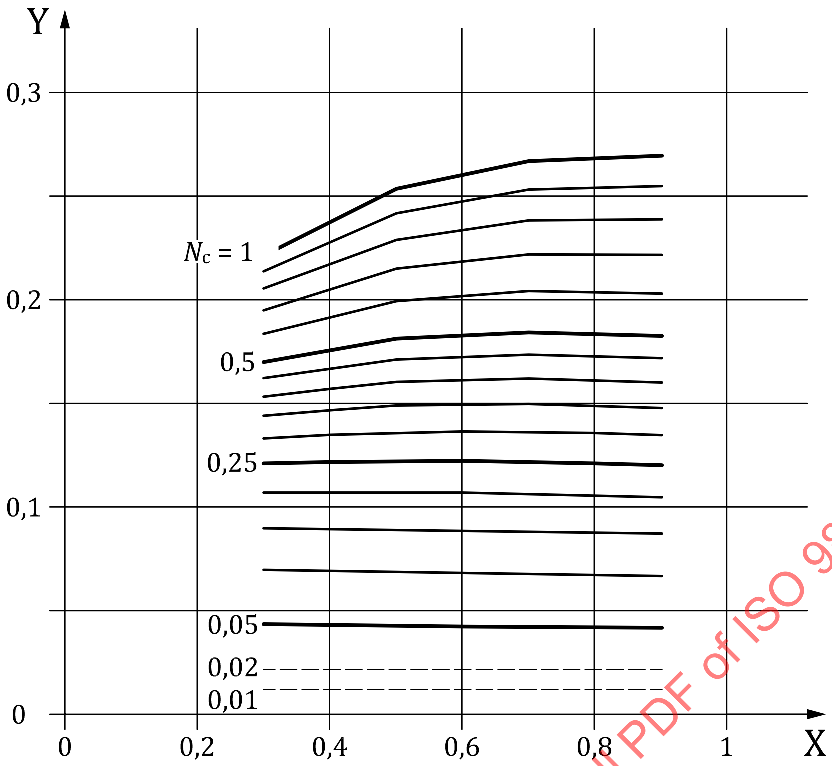
θ_k is the temperature at each depth [°C];

$\theta_{\mathrm{s,i}}$ is the surface temperature of the insertion side of the insulation material [°C];

$\theta_{\mathrm{s,o}}$ is the surface temperature of the opposite surface to the insertion side of the insulation material [°C];

x_k^{*} is the depth from the surface of the insulation material on the insertion side divided by the thickness of the insulation material [-]. $\left(1 - x_k^{*}\right)$ is the non-dimensional estimated temperature in the insulation material.

f) The non-dimensional temperature deviation at each depth is plotted in Figure A.1, and when the value falls below a certain curve at all depths, the magnitude of influence of the thermal bridge effect is evaluated by the numerical value (N_c value) attached to the minimum curve.



Key

X non-dimensional depth

Y non-dimensional temperature deviation [−]

Figure A.1 — Temperature distribution chart for evaluation of the thermal bridge effect of the temperature sensor rod

g) The N_c value obtained in step f) is converted to the nominal N_c value, i.e. the expected value of N_c when the thermal conductivity and the thickness of the insulation material are 0,03 W/(mK) and 0,05 m, respectively, using Formula (A.2):

$$N_{c,nom} = \frac{k_m}{k_{m,nom}} \times \left(\frac{L}{L_{nom}} \right)^2 \times \frac{\ln(2L_{nom}/\phi_s)}{\ln(2L/\phi_s)} \times N_c \tag{A.2}$$

where

$N_{c,nom}$ is the nominal N_c value of the sensor rod tested [-];

k_m is the thermal conductivity of the insulation material [W/(mK)];

$k_{m,nom}$ is the nominal thermal conductivity of the insulation material (=0,03[W/(mK)]);

L is the thickness of the insulation material [m];

L_{nom} is the nominal thickness of the insulation material (=0,05 m);

ϕ_s is the diameter of the sensor rod tested [m];

N_c is the dimensionless number obtained in step f) [-].

A.5 Uncertainty

A.5.1 General

This clause describes a procedure for evaluating the uncertainty of the nominal N_c value of the sensor rod tested and an example of its calculation. The calculation example is not part of this document.

A.5.2 Mathematical description

a) Non-dimensional temperature deviation

The non-dimensional temperature deviation is calculated according to Formula (A.1). x_k^* in Formula (A.1) is shown in Formula (A.3):

$$x_k^* = \frac{x_k}{L} \quad \text{(A.3)}$$

where

x_k is the depth from the surface of the insulating material on the insertion side [m];

L is the thickness of the insulation material [m].

Using the measurement variables, the non-dimensional temperature deviation at the depth of x_k is expressed in Formula (A.4) as:

$$\theta_{\mathrm{d},k}^* = \frac{\theta_k - \theta_{\mathrm{s,o}}}{\theta_{\mathrm{s,i}} - \theta_{\mathrm{s,o}}} - \left(1 - \frac{x_k}{L}\right) \quad \text{(A.4)}$$

b) Nominal N_c value of the sensor rod tested

The nominal N_c value of the sensor rod tested is calculated according to Formula (A.2). N_c in Formula (A.2) is expressed as a function of

$$N_c = \left(\theta_{\mathrm{d},k}^* + 0{,}023\right) / 0{,}085 \quad \text{(A.5)}$$

NOTE Formula (A.5) approximates the relationship between the N_c value and the non-dimensional temperature deviation at the non-dimensional depth of 0,9 in Figure A.1. In practice, the N_c value is calculated based on the results of temperature measurements at multiple depths using Figure A.1, but due to the correlation between the variations of measurements at different depths, a function to derive the N_c value from the non-dimensional temperature deviation at a single depth is used for the uncertainty analysis.

Using the measurement variables, the nominal N_c value of the sensor rod tested is expressed as Formula (A.6):

$$N_{\mathrm{c,nom}} = \frac{k_{\mathrm{m}}}{k_{\mathrm{m,nom}}} \times \left(\frac{L}{L_{\mathrm{nom}}}\right)^2 \times \frac{\ln(2L_{\mathrm{nom}} / \phi_{\mathrm{s}})}{\ln(2L / \phi_{\mathrm{s}})} \times \frac{\theta_{\mathrm{d},k}^* + 0{,}023}{0{,}085} \quad \text{(A.6)}$$

A.5.3 Uncertainty estimation

a) Non-dimensional temperature deviation

The standard uncertainty of the non-dimensional temperature deviation is calculated by Formula (A.7):

$$u\left(\theta_{\mathrm{d},k}^*\right) = \sqrt{c_{\theta_k}^2 \times u^2(\theta_k) + c_{\theta_{\mathrm{s,i}}}^2 \times u^2(\theta_{\mathrm{s,i}}) + c_{\theta_{\mathrm{s,o}}}^2 \times u^2(\theta_{\mathrm{s,o}}) + c_{x_k}^2 \times u^2(x_k) + c_L^2 \times u^2(L)} \quad \text{(A.7)}$$

assuming that each measurement variable is independent of the others, where

$u(\theta_k)$ is the uncertainty in measuring the temperature at each depth [°C];

$u(\theta_{s,i})$ is the uncertainty in measuring the surface temperature of the insertion side of the insulation material [°C];

$u(\theta_{s,o})$ is the uncertainty in measuring the surface temperature of the opposite surface to the insertion side of the insulation material [°C];

$u(x_k)$ is the uncertainty in measuring the depth from the surface of the insulation material on the insertion side [m];

$u(L)$ is the uncertainty in measuring the thickness of the insulation material [m];

c_i is the sensitivity coefficient for measurement variable *i*.

b) Nominal N_c value of the sensor rod tested

The standard uncertainty of the nominal N_c value of the sensor rod tested is calculated by Formula (A.8):

$$u\left(N_{c,nom}\right)=\sqrt{c_{k_m}^2 \times u^2\left(k_m\right)+c_L^2 \times u^2(L)+c_{\phi_s}^2 \times u^2\left(\phi_s\right)+c_{\theta_{d,k}^*}^2 \times u^2\left(\theta_{d,k}^*\right)/N_s} \quad (A.8)$$

assuming that each variable is independent of the others, where

$u(k_m)$ is the uncertainty in measuring the thermal conductivity of the insulation material [W/(mK)];

$u(L)$ is the uncertainty in measuring the thickness of the insulation material [m];

$u(\phi_s)$ is the uncertainty in measuring the diameter of the sensor rod tested [m]

$u\left(\theta_{d,k}^*\right)$ is the uncertainty of the non-dimensional temperature deviation [-];

N_s is the number of samplings at different locations of the specimen [-];

c_i is the sensitivity coefficient for measurement variable *i*.

A.5.4 Example of calculation of uncertainty estimation

Table A.1 shows an example of the results of an evaluation of the uncertainty of the non-dimensional temperature deviation at the depth of 4/5 of the insulation thickness. The uncertainty in measuring the insulation thickness is ignored here.

Table A.2 shows an example of the results of an evaluation of the uncertainty of the nominal N_c of the sensor rod tested. The combined standard uncertainty of the non-dimensional temperature deviation calculated from Table A.1 is used assuming that three measurements at different test positions of the insulation material are performed. Uncertainties related to the sensor diameter and the insulation thickness are ignored here.