BRITISH STANDARD

BS EN 12939:2001
Incorporating Corrigendum No. 1

Thermal performance of building materials and products — Determination of thermal resistance by means of guarded hot plate and heat flow meter methods — Thick products of high and medium thermal resistance

The European Standard EN 12939:2001 has the status of a British Standard

ICS 91.100.60

British Standards

National foreword

This British Standard is the official English language version of EN 12939:2000. This British Standard together with BS EN 12664:2001 and BS EN 12667:2001 supersedes BS 874-2.1:1986 and BS 874-2.2:1998 which are withdrawn.

The UK participation in its preparation was entrusted by Technical Committee RHE/9, Thermal insulating materials, to Subcommittee RHE/9/2, Thermal properties of insulating materials, which has the responsibility to:

- aid enquirers to understand the text;
- present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;
- monitor related international and European developments and promulgate them in the UK.

A list of organizations represented on this subcommittee can be obtained on request to its secretary.

Cross-references

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English version

Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Thick products of high and medium thermal resistance

Performance thermique des matériaux et produits pour le bâtiment - Détermination de la résistance thermique par la méthode de la plaque chaude gardée et la méthode fluxmétrique - Produits épais de haute et moyenne résistance thermique

Wärmetechnisches Verhalten von Baustoffen und Bauprodukten - Bestimmung des Wärmedurchlasswiderstandes nach dem Verfahren mit dem Plattengerät und dem Wärmestrommessplatten-Gerät - Dicke Produkte mit hohem und mittlerem Wärmedurchlasswiderstand

This European Standard was approved by CEN on 18 October 2000.

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Contents

Foreword

This European Standard has been prepared by Technical Committee CEN/TC 89 "Thermal performance of buildings and building components", the secretariat of which is held by SIS.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by May 2001, and conflicting national standards shall be withdrawn at the latest by May 2001.

This European Standard has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association, and supports essential requirements of EU Directive(s).

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

The annexes A and B are normative. The annexes C and D are informative.

Introduction

This standard is intended to complement EN 12667. It addresses specific problems when testing, according to European product standards, thick high and medium thermal resistance specimens with a heat flow meter or guarded hot plate.

In this standard the references to ISO 8301:1991 and ISO 8302:1991 are limited to some experimental procedures and to the error analysis. The guarded hot plate and heat flow meter methods are described in EN 12667; assessment procedures are described in EN 1946-2:1999 and EN 1946-3:1999.

A CEN Report CR xxx, The use of interpolating equations in relation to measurements on thick specimens, (under preparation) supplies additional information on the use of interpolating functions to predict the thickness effect.

Among existing apparatus for steady state thermal testing, guarded hot plate apparatus and heat flow meter apparatus can be operated up to specimen thicknesses of 100 mm to 150 mm if the accuracy has to be kept within 2 % (and possibly 1 %), while the accuracy of guarded and calibrated hot box apparatus, which can test thicker specimens, is not as good as that of the previously mentioned two test apparatus.

As the thickness of many insulating products exceeds 100 mm to 150 mm, there is a need for a testing procedure that will supply enough information to predict the thermal performance of insulation products at their actual thicknesses. Different options are offered in this standard; the most appropriate one may be indicated in product standards.

When the thickness effect is relevant, i.e. when the thermal resistance of a thick product cannot be calculated as the sum of the thermal resistances of slices cut from the product, some material parameters are determined for use in interpolating equations. The procedure to determine these parameters is split into preliminary and routine measurements and evaluations, see C.1.

Background information and additional information on the use of interpolating equations is to be found in CR xxx.

1 Scope

This standard gives the procedures to determine the thermal resistance of products the thicknesses of which exceed the maximum thickness for guarded hot plate or heat flow meter apparatus. In any case most of the procedures described in this standard require apparatus that allows tests on specimens up to 100 mm thick.

This standard gives guidelines to assess the relevance of the thickness effect, i.e. to establish whether the thermal resistance of a thick product can or cannot be calculated as the sum of the thermal resistances of slices cut from the product, these guidelines complement the indications given in ISO 8302:1991 on the guarded hot plate apparatus.

This standard describes testing conditions which prevent the onset of convection. which could take place in some products under the considered temperature differences and thicknesses.

2 Normative references

This standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies (including amendments).

EN 1946-2:1999	Thermal performance of building products and components - Specific criteria for the assessment of laboratories measuring heat transfer properties – Part 2: Measurements by guarded hot plate method
EN 1946-3:1999	Thermal performance of building products and components - Specific criteria for the assessment of laboratories measuring heat transfer properties – Part 3: Measurements by heat flow meter method
EN 12667:-[1)]	Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Products of high and medium thermal resistance
EN ISO 7345	Thermal insulation - Physical quantities and definitions (ISO 7345:1987)
EN ISO 9288	Thermal insulation - Heat transfer by radiation - Physical quantities and definitions (ISO 9288:1989)
ISO 8301:1991	Thermal insulation - Determination of steady-state thermal resistance and related properties - Heat flow meter apparatus
ISO 8302:1991	Thermal insulation - Determination of steady-state thermal resistance and related properties - Guarded hot plate apparatus

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[1] To be published

3 Definitions, symbols and units

3.1 Terms and definitions

For the purposes of this standard the terms and definitions given in EN ISO 7345 and EN ISO 9288 apply.

NOTE EN ISO 9288 defines spectral directional extinction, absorption and scattering coefficients and the spectral directional albedo only, while this standard makes use of total hemispherical coefficients, which can be obtained by the previous ones by appropriate integrations.

3.2 Symbols and units

Symbol	Quantity	Unit
A	conduction parameter	W/(m·K)
B	solid conduction parameter	m^{3}/kg
C	radiation parameter	W·m^{2}/(kg·K)
E	extinction parameter for combined conduction and radiation	m^{-1}
F	complement to unity of the "two flux model" albedo	
L	thickness effect parameter	
R	thermal resistance	m^{2}·K/W
R_0, R_{01}, R_{02}	extrapolated thermal resistance at zero thickness	m^{2}·K/W
T	thermodynamic temperature	K
T	transfer factor d/R (of a specimen)	W/(m·K)
Z	emissivity parameter	
d	thickness	m
d_b	mean bead or grain diameter	m
d_∞	thickness beyond which thermal resistance becomes linear	m
e	edge temperature ratio	
h_r	radiative heat transfer surface coefficient	W/(m^{2}·K)
q	density of heat flow rate	W/m^{2}
q_r	density of radiative heat flow rate	W/m^{2}
q_t	total density of heat flow rate	W/m^{2}
t	time	s
β'_*	mass extinction parameter	m^{2}/kg

Symbol	Quantity	Unit
ε	emissivity	
λ	thermal conductivity	W/(m·K)
λ_a	thermal conductivity of air	W/(m·K)
λ_g	thermal conductivity of gas	W/(m·K)
λ_r	radiativity (of a material)	W/(m·K)
λ_{cd}	combined gaseous and solid thermal conductivity (of a material)	W/(m·K)
λ_t	thermal transmissivity (of a material) $\Delta d/\Delta R$	W/(m·K)
θ	Celsius temperature	°C
ρ	density	kg/m^3
ρ_s	density of the solid matrix	kg/m^3
σ_n	Stefan-Boltzmann constant	W/(m^2·K^4)
ϖ^*	two-flux model albedo	

4 Instrumentation

4.1 General

The apparatus used for the measurements shall be a guarded hot plate or heat flow meter conforming with the requirements of EN 12667. This standard gives neither relevant design criteria and proven performance checks nor the determination of apparatus emissivity; these, as well as specific apparatus requirements applicable to the procedures described in this standard, are to be found either in EN 1946-2:1999 or EN 1946-3:1999, according to the apparatus used. Only those apparatus requirements affecting specimen sizes and tolerances are given in this standard.

When it is not explicitly stated otherwise, guarded hot plate apparatus requirements are assumed to be applicable also to heat flow meter apparatus.

Some recommended sizes and tolerances are supplied in this standard. In 4.2 and 4.3 requirements for common testing conditions are specified. More information is given in annex A.

4.2 Maximum specimen thickness

The maximum specimen thickness should be according to EN 12667, see limit values in its table A.1 for some common apparatus sizes. See also annex A of this standard for more information concerning low density specimens.

4.3 Minimum specimen thickness, flatness tolerances

The procedures described in this standard may require measurements at the minimum allowed specimen thickness (which depends upon apparatus parameters and testing conditions). The requirements of A.3.3 of EN 12667 shall be met, extending them for a thermal resistance of the specimen as low as 0,3 $m^2 \cdot K/W$. The following two testing conditions shall be considered in relation to this standard for both guarded hot plate and heat flow meter apparatus:

a) Tests on non rigid specimens achieving a good contact with the apparatus and whose thermal resistance is greater than or equal to 0,3 $m^2 \cdot K/W$, e.g. mineral wool boards or elastomeric cellular boards. In this case the departures from a true plane result in an error in the measurement of specimen thickness. This error shall be less than 0,5 % (see table A.1 of EN 12667). For detailed information see annex A of this standard.

b) Tests on rigid specimens having a thermal resistance greater than or equal to 0,3 $m^2 \cdot K/W$, e.g. polystyrene or rigid polyurethane boards. In this case the departures from a true plane are the source of contact resistances; these shall be less than 0,5 % of the specimen thermal resistance (see table A.2 of EN 12667).

This standard does not cover special testing techniques (use of contact sheets) to be applied when the thermal resistance of the specimen is less than 0,3 $m^2 \cdot K/W$.

5 Procedures

5.1 General

Specimen preparation and handling shall be in accordance with EN 12667. Specific specimen preparation should be found in the appropriate product standard referencing the procedures described in this standard.

5.2 Introductory considerations

The thermal resistance R of a specimen of low density insulating materials may be written as follows:

$$R = R_0 + d/\lambda_t \tag{1}$$

(where R_0 is the extrapolated thermal resistance at zero thickness) and the transfer factor T is defined as follows:

$$\mathrm{T} = \lambda_t \frac{1}{1 + \frac{\lambda_t}{d} R_0} \tag{2}$$

NOTE 1 For the derivation of equations (1) and (2) and their graphical representation see CR xxx.

The procedures described in this standard can be grouped as follows:

1) preliminary procedures to assess whether the thickness effect is relevant;

2a) procedures applicable when the thickness effect is not relevant;

2b) procedures applicable when the thickness effect is relevant.

The procedures described apply to products having thicknesses exceeding d_∞, with the exception of the use of tables 3 and 4, which also include thicknesses below d_∞. The procedures further assume that products are sufficiently homogeneous, such that no individual value of measured thermal resistance will deviate by more than 0,7 % from the interpolating straight line. When these conditions are not satisfied or when there is a need to keep the number of measurements to a minimum, annex C should be consulted for guidance. A flow-chart showing testing options is given in figure 1.

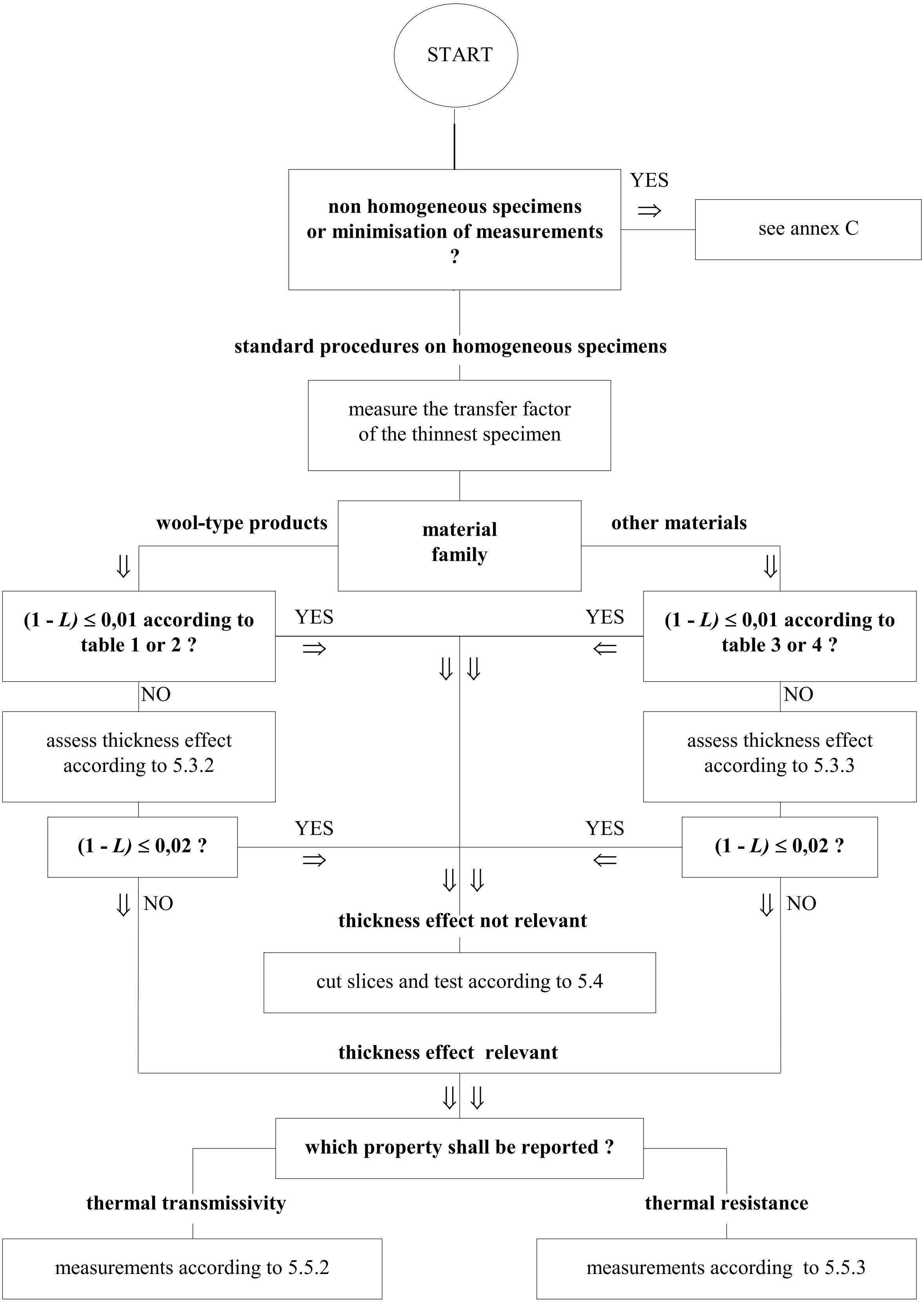


Figure 1 - Procedures to test thick specimens

NOTE 2 Due to the different mechanism of the radiation extinction, the procedures of this standard are differentiated by material families.

NOTE 3 The large amount of work required by the experimental procedures to assess the relevance of the thickness effect suggests they should be reduced to the absolute minimum needed. A thorough understanding of the influence of material parameters and their evaluation allows routines to be developed that require far less experimental work even though far more sophisticated. For this purpose some theoretical calculations based on just one measured value of the thermal resistance of a specimen are supplied in C.2.

NOTE 4 Even though this standard gives procedures to determine product thermal resistance at thicknesses that exceed guarded hot plate or heat flow meter capabilities, those applicable to materials exhibiting a relevant thickness effect can equally be applied to materials produced in thicknesses falling within apparatus capabilities, to allow the interpolation of product thermal resistances from measurements at few product thicknesses only.

NOTE 5 Specific procedures are described for products that have density gradients along the thickness, see C.3.2.1.2 for mineral wool, or have the density increasing quite sharply towards both product surfaces (skin products), see C.3.2.2.3 for cellular-plastic skin-products. Nevertheless, even for these products, the preliminary procedures of 5.3 apply.

All the procedures intended to characterise specimens having a thickness exceeding apparatus capabilities require a preliminary evaluation of the relevance of the thickness effect, i.e. how far from unity is the ratio $L = \mathsf{T}/\lambda_t$ between the transfer factor and thermal transmissivity.

NOTE 6 The difference (1 - L) may be of greater interest than L because (1 - L) is zero when the thickness effect has no relevance.

5.3 The relevance of the thickness effect

5.3.1 General

If $(1 - L) = R_0/R \leq 0{,}02$, the thickness effect is not relevant for the product considered and the procedure of 5.4 shall be used. Otherwise elementary material-dependent procedures are given in 5.3.2 and 5.3.3 for routine and control purposes.

NOTE 1 The range of thicknesses of the products made of one material should be considered: if the largest product thickness is lower than the maximum allowed specimen thickness for the apparatus to be used and the relevance of the specimen thickness is to be assessed, the procedure in 3.4.2 of ISO 8302:1991 can be used.

NOTE 2 The simplest assessment of the relevance of the thickness effect is for materials containing air within their solid matrix, because tables or a graph can be used, see e.g. C.2.2.1.

5.3.2 Procedure for wool-type products

Measure the transfer factor of the product of the smallest thickness.

a) If, according to the data of table 1 for mineral wool or table 2 for wood wool, $(1 - L) \leq 0{,}01$, the thickness effect may be considered not relevant.

b) If $(1 - L) > 0{,}01$ according to table 1 for mineral wool or table 2 for wood wool, assess the relevance of the thickness effect as follows:

1) As a minimum three measurements shall be made:
   - close to the maximum allowed apparatus thickness;
   - at the minimum product thickness or at a thickness approximately one third of the maximum allowed specimen thickness (by slicing a specimen), whichever is smaller;
   - at a thickness approximately the mean of the above two.

   EXAMPLE A material is produced in thicknesses of 80 mm, 120 mm and 200 mm; the maximum allowed apparatus thickness is 120 mm. The measurements are taken at 120 mm, 80 mm and 40 mm (by slicing a thicker product).

2) Through linear regression compute R_0 and λ_t; using equation (2) compute the transfer factor at the minimum product thickness and from this the ratio $L = \mathrm{T}/\lambda_t$. Check whether $(1 - L) \leq 0{,}02$.

When mineral wool products have density gradients in the thickness direction, the data of table 1 shall be applied by introducing the transfer factor measured on a slice having the lowest density found in an actual inhomogeneous product.

For products having density inhomogeneities or density gradients in the thickness direction, that generate deviations of measured thermal resistance from a straight line exceeding 0,7 %, annex C may be consulted for guidance.

5.3.3 Procedures for other materials

Measure the transfer factor of the product of the smallest thickness and if, according to the data of table 3 for polystyrene or the data of table 4 for insulating cork boards, $(1 - L) \leq 0{,}01$, assume that the thickness effect is not relevant.

If $(1 - L) > 0{,}01$ according to table 3 for expanded polystyrene or table 4 for insulating cork boards, and in any case for any other material, assess the relevance of the thickness effect as follows:

a) Make three or preferably more thermal resistance measurements, starting from a specimen having a thickness close to the maximum allowed apparatus thickness and then cutting away slices and retesting the remaining part of the specimen. Measurements shall be taken:

   - close to the maximum allowed apparatus thickness;
   - at a thickness preferably between 10 mm and 15 mm or at least at the lowest allowed apparatus thickness;
   - at one or more thicknesses between the above two, one of which approximately twice the one indicated in the second dash above.

b) If there are at least three measurements among those indicated in a) that can be interpolated by a straight line within 0,7 %, using linear regression, compute R_0 and λ_t; through equation (2) compute the transfer factor at the minimum product thickness and from this the ratio $L = \mathrm{T}/\lambda_t$ (otherwise take measurements at additional thicknesses or C.3.2.2 should be consulted).

c) Check whether $(1 - L) \leq 0{,}02$.

When the extrusion process of a cellular plastic material results in a product with much higher density at the surfaces of the product looking like a skin, the core material (that it is expected to be quite homogeneous) shall be tested.

5.4 Procedures when the thickness effect is not relevant

- When the thickness effect is not relevant according to 5.3, from the above procedure determine the minimum thickness for which $(1 - L) \leq 0{,}01$.

- Cut the product in slices not thinner than the thickness so defined.

  NOTE When deciding whether an apparatus is suitable to use this procedure, the above thickness can also be regarded as the minimum value for the maximum allowed specimen thickness of the apparatus to be used.

  Cutting, e.g. with a band saw, may remove a layer of material from each slice. If this is the case, the measured thermal resistance of the cut slice shall be corrected. If not otherwise specified in a product standard, the slice thermal resistance is that of the cut slice increased by a percentage equal to that of the thickness of the removed layer referred to the cut slice thickness.

- Compute the total specimen thermal resistance as the sum of the thermal resistances of the slices, making appropriate allowance for the material lost during cutting.

Consult product standards for advice on whether it is acceptable to compute the total thermal resistance of the specimen as the product of the thermal resistance of one slice and the number of equal slices composing the specimen, or whether each slice shall be tested and the total thermal resistance of the specimen computed as the sum of the thermal resistances of the slices.

When the thickness effect is not relevant for an inhomogeneous mineral wool product (e.g. having density gradients in the direction of the thickness) or is not relevant for products made of cellular plastic materials in which the extrusion process produced much higher density at the surfaces of the product (like a skin), then:

- Cut the product in slices not thinner than the thickness for which $(1 - L) = 0{,}01$.

- Measure the thermal resistance of each slice.

- Compute the product thermal resistance by adding the measured thermal resistance of each slice, making appropriate allowance if some material is lost during cutting, see above.

5.5 Procedures when the thickness effect is relevant

5.5.1 General

If the thickness is relevant, consult the relevant product standard about the possibility of choosing between the determination of the thermal transmissivity of the material or the thermal resistance of the product.

Product standards may allow the use of the values of L derived from table 1, table 2, table 3 or table 4 to compute the thermal transmissivity from the measured transfer factor of a product slice or from the average transfer factor of all the slices cut from the product.

5.5.2 Determination of the thermal transmissivity of the material

If there is a product such that for its thickness $(1 - L) \leq 0{,}01$ and its thickness is not greater than the maximum allowed apparatus thickness, take a specimen from this product, test the specimen and take the thermal transmissivity of the material as equal to the measured transfer factor of the specimen.

If such a product does not exist, consult product standards for advice on whether λ_t shall be obtained by linear interpolation of the measurements indicated in 5.3 or whether all the slices cut from the product shall be tested and the measured data introduced in the linear regression to derive λ_t.

When the linear regression is applied to three measured data, as indicated in 5.3, the worst case relative error on the calculated thermal transmissivity is $2\ \Delta R/(R_M - R_m)$, where ΔR is the maximum absolute error in measured thermal resistances, while R_M and R_m are the largest and smallest measured thermal resistances respectively (see also 5.5.3). If the error on the calculated thermal transmissivity is too large (e.g. > 1 %), the number of measurements shall be increased and appropriate statistics shall be applied to evaluate the resulting error.

When some or all of the data have been measured on specimens having thicknesses lower than d_∞ (e.g. for some low density expanded polystyrene products), a linear interpolation is not possible and the regression shall be applied to the equations given in annex B. See annex C for more guidance in this situation.

5.5.3 Determination of the thermal resistance of the products

The thermal resistance of products exceeding apparatus capabilities shall be computed using equation (1) (and the transfer factor using equation (2)). Consult product standards for advice on whether R_0 and λ_t, to derive R, shall be obtained by linear interpolation of the measurements indicated in 5.3 or whether all the slices cut from the product shall be tested and the measured data introduced in the linear regression to derive R_0 and λ_t.

When the linear regression is applied to three measured data, as indicated in 5.3, the worst case error ΔR_e in the extrapolated thermal resistance R_e at the thickness d_e is such that $\Delta R_e/R_e = 2\ \Delta R/(R_M - R_m)\times[1 - (R_M + R_m)/(2\ R_e)]$ where ΔR is the maximum error in measured thermal resistances, while R_M and R_m are the largest and smallest measured thermal resistances respectively. For the relative error $\Delta R_e/R_e$, $\Delta R/R_M \leq \Delta R_e/R_e \leq 2\ \Delta R/(R_M - R_m)$. The lower limit $\Delta R/R_M$ applies when $R_e \approx R_M$, while the upper limit $2\ \Delta R/(R_M - R_m)$ applies when $R_e >> R_M$. If the relative error $\Delta R_e/R_e$ is too large (e.g. > 1 %), the number of measurements shall be increased and appropriate statistics shall be applied to evaluate the resulting error.

When some or all the data were measured on specimens having thicknesses lower than d_∞ (e.g. for some low density expanded polystyrene products) a linear interpolation is not possible and the regression shall be applied to the equations given in annex B. See annex C for more guidance in this situation.

6 Calculations and test report

Calculations of measured heat transfer properties shall be according to clause 8 of EN 12667; the general layout of the report shall be in accordance to clause 9 of EN 12667. Information on the procedures derived from this standard and related data and calculations shall be according to the relevant product standard referencing this standard.

Table 1 - Thickness effect parameter for mineral wool

Transfer factor T mW/(m·K)	**Specimen thickness** *D* Mm	**Thickness effect parameter** *L*
50	40	0,952 to 0,957
	80	0,978 to 0,980
	200	0,991 to 0,993
45	40	0,970 to 0,973
	80	0,986 to 0,988
	200	0,993 to 0,996
40	40	0,983 to 0,987
	80	0,991 to 0,994
	200	0,996 to 0,998
35	20	0,986 to 0,993
	40	0,993 to 0,997
	80	0,996 to 0,999
	200	0,998 to 1,000

Table 2 - Thickness effect parameter for wood wool

Transfer factor T mW/(m·K)	**Specimen thickness** *d* mm	**Thickness effect parameter** *L*
65	30	0,906 to 0,921
	50	0,945 to 0,955
	100	0,972 to 0,977
55	15	0,885 to 0,925
	30	0,953 to 0,969
	50	0,973 to 0,983
	100	0,986 to 0,992
50	15	0,935 to 0,965
	30	0,972 to 0,985
	50	0,983 to 0,992
	100	0,991 to 0,997
46	15	0,962 to 0,985
	30	0,980 to 0,992
	50	0,985 to 0,995
	100	0,991 to 0,997

Table 3 - Thickness effect parameter for expanded polystyrene

Transfer factor T mW/(m·K)	**Specimen thickness** *D* Mm	**Thickness effect parameter** *L*
43	20	0,805 to 0,815
	40	0,905 to 0,910
	100	0,965 to 0,970
40	20	0,855 to 0,870
	40	0,930 to 0,940
	100	0,970 to 0,980
35	20	0,935 to 0,945
	40	0,965 to 0,980
	100	0,985 to 0,990
32	20	0,970 to 0,985
	40	0,985 to 0,995
	100	0,995 to 0,999

Table 4 - Thickness effect parameter for insulating cork boards

Transfer factor T mW/(m·K)	**Specimen thickness** *D* Mm	**Thickness effect parameter** *L*
47	40	0,890 to 0,909
	100	0,959 to 0,962
	200	0,977 to 0,981
40	20	0,896 to 0,921
	40	0,948 to 0,962
	100	0,981 to 0,984
	200	0,990 to 0,994
35	20	0,958 to 0,976
	40	0,977 to 0,988
	100	0,993 to 0,996
	200	0,996 to 0,998
33	20	0,979 to 0,992
	40	0,985 to 0,995
	100	0,995 to 0,997
	200	0,996 to 0,998

Annex A (normative)

Instrumentation

A.1 Type of apparatus

When it is not explicitly stated otherwise, guarded hot plate apparatus requirements are assumed as applicable also to the heat flow meter apparatus.

A.2 Guarded hot plate

A.2.1 Guarded hot plate apparatus requirements and equipment performance check

Annex B of EN 12667 summarises apparatus requirements. According to EN 1946-2:1999, equipment design and error analysis shall be in accordance with 2.1, 2.2 and 2.3 of ISO 8302:1991. The equipment performance check shall be in accordance with 4.5 of EN 1946-2:1999

A.3 Heat flow meter

A.3.1 Heat flow meter apparatus requirements, calibration and equipment performance check

Annex C of EN 12667 summarises apparatus requirements. According to EN 1946-3:1999, equipment design and error analysis shall be in accordance with 2.1, 2.2 and 2.3 of ISO 8301. The calibration shall be in accordance with 4.5 of EN 1946-3:1999 and equipment performance check shall be in accordance with 4.6 of EN 1946-3:1999.

A.4 Maximum specimen thickness

Table A.1 in EN 12667 shows, for some apparatus dimensions, the maximum allowed specimen thickness when some testing conditions are satisfied. That information is based on purely conductive models. For low density materials (e.g. less than 20 kg/m^3), where a considerable amount of radiation heat transfer takes place, it is yet to be established how effectively gradient guards can control lateral losses, and it is advisable not to exceed the thicknesses allowed from the data of table A.1 in EN 12667, unless the calculations of edge heat loss errors include coupled conduction and radiation heat transfer. The adverse effect of radiation heat transfer on edge heat loss error can be understood by comparing the two sets of data of table A.1 of this standard: they correspond to the two extremes of pure conduction in the specimen and pure radiation if the space occupied by the specimen were left void. The value $e = 0$ corresponds to the minimum edge heat loss error for pure radiation (as e close to 0,5 corresponds to the minimum edge heat loss error for pure conduction in the specimen).

> NOTE The parameter e is defined as the ratio of the temperature difference between the edge, assumed at uniform temperature, and the cold side of the specimen to the temperature difference between hot and cold sides of the specimen.

The information given in this clause is also based on an assumption of isotropic specimens, and it is not suitable to assess the instrument performance for equipment intended to test highly non-isotropic or layered specimens.

Table A.1 - Errors due to edge heat losses by pure conduction or pure radiation

Dimensions in millimetres

Overall Size	**Metering section**	**Guard width**	**Specimen thickness** 40	50	60	80	100	120	160	200
Pure conduction, $e = 0$										
500	300	100	0,01 %	0,08 %	0,27 %	1,35 %	3,75 %	--	--	--
500	200	150	0,00 %	0,01 %	0,03 %	0,28 %	1,10 %	2,84 %	9,72 %	--
Pure radiation, $e = 0$										
500	300	100	3,3 %	5,1 %	--	--	--	--	--	--
500	200	150	2,5 %	3,8 %	5,5 %	--	--	--	--	--

A.5 Minimum specimen thickness, flatness tolerances

A.5.1 Thickness error and minimum specimen thickness of non rigid specimens

When testing non rigid specimens in good contact with the apparatus, the departures from a true plane can be considered directly an error in the measurement of specimen thickness. This error is the consequence of departures from a true plane of specimen surfaces resulting from departures from a true plane of apparatus surfaces.

The worst case condition resulting from flatness tolerances is at the minimum measurable thickness, d_m, when both hot and cold surfaces are either dished or bowing, see figure A.1. If p is the flatness tolerance expressed as maximum distance of one apparatus surface from a true plane, the average thickness error for each apparatus surface is $p/2$. Considering then both apparatus surfaces in contact with the specimen, the thickness error is p.

According to EN 12667, if G is the overall size of the apparatus, i.e. the external side of the guard, the maximum allowed flatness tolerance, p, should not exceed 0,025 % of G i.e. $100\,p/G = 0{,}025$, see the fifth column of table A.1 of EN 12667. Due to the limit on thickness error, $100\,p/d_m \le 0{,}5$. The minimum specimen thickness, d_m, is then limited by flatness tolerances and shall be not less than 5 % of G, see the sixth column of table A.1 of EN 12667.

When the minimum specimen thickness of the eighth column of table A.1 of EN 12667 (related to the maximum allowed gap width) is larger than that of the sixth column, the actual gap width shall be checked to ensure that the minimum specimen thickness is not less than 10 g. In the opposite case only better flatness tolerances allow tests at the minimum specimen thickness dependent on the gap width.

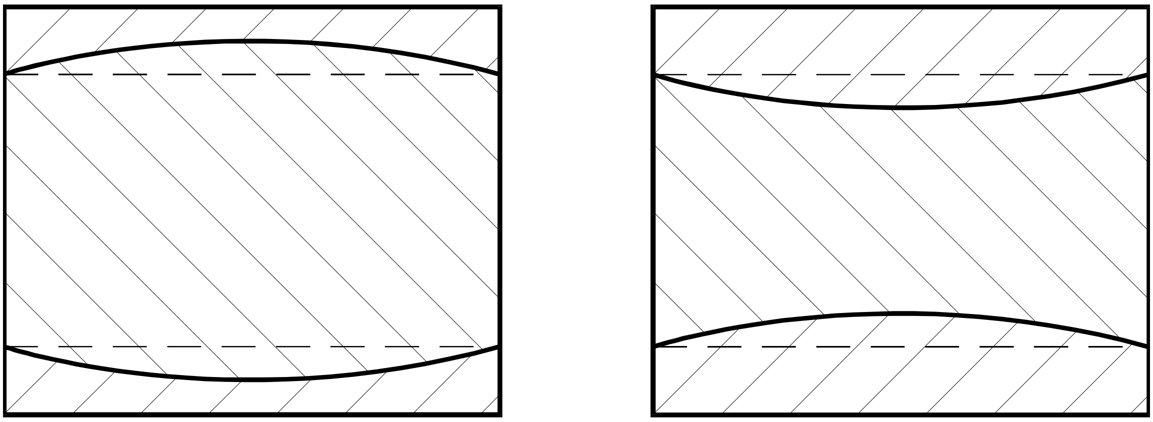
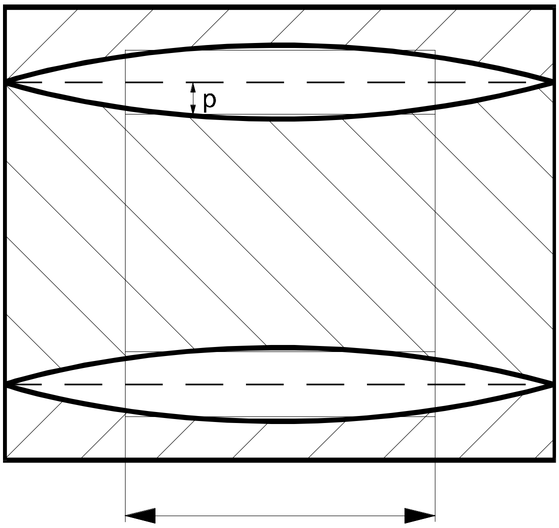


Figure A.1 - Non rigid specimens



Key

1 Metering area

Figure A.2 - Rigid specimens

A.5.2 Contact resistances and flatness tolerances of rigid specimens

When testing rigid specimens, a thermal resistance due to the air pockets (on both sides of the specimen as in figure A.2 in worst case conditions) is created by departures from a plane (contact resistance). Around room temperature (the thermal conductivity of air is close to 0,025 W/(m·K)) the maximum allowed equivalent air layer resulting from the air pockets on both sides of the specimen and inclusive of the effect of both apparatus and specimen departures from a true plane has been computed and is given in table A.2 of EN 12667.

NOTE Table A.2 of EN 12667 shows that the required levels of flatness for both the specimen and apparatus surfaces are stringent and not related to the apparatus size.

Annex B (normative)

Conversion utilities for thick specimens

B.1 General

All testing procedures to evaluate the thermal performance of thick specimens require utilities which are essentially based on interpolating functions containing a number of material parameters and testing conditions. Interpolating functions and material parameters are not the same for all materials. Common interpolating functions are presented in B.2.1, which is followed by separate equations for each material family.

> NOTE A presentation of essential phenomena and applicable limits for the use of interpolating functions is given in CR xxx.

B.2 Interpolating functions

B.2.1 Interpolating functions applicable to any product

The following equations, describing heat transfer when testing low density **homogeneous** insulating materials, shall be used in this standard as interpolating tools. The use of these equations also for some inhomogeneous materials is described in annex C. A special case on mineral wool with uniform density gradients is considered in B.2.2.2.

The thermal resistance, R, of a flat specimen of low density material can be expressed as:

$$R = R_0' + d/\lambda_t \qquad (B.1)$$

where R_0' is not necessarily independent of the thickness d, as it is in equation (1), and

$$\lambda_t = \lambda_{cd} + \lambda_r \qquad (B.2)$$

where

λ_t is the thermal transmissivity;
λ_{cd} is the combined gaseous and solid thermal conductivity;
λ_r is the radiativity.

If T_m is the mean test thermodynamic temperature, $\sigma_n = 5{,}6699 \times 10^{-8}$ W/(m^2·K^4) the Stefan-Boltzmann constant, ε the total hemispherical emissivity of the apparatus, β'_* a mass extinction parameter, ω_* an albedo, ρ the bulk density of the material and the following expressions are introduced

$$F = (1 - \omega_*) \qquad h_r = 4\,\sigma_n\,T_m^3 \qquad (B.3)$$

The radiativity, λ_r, is expressed as follows:

$$\lambda_r = \frac{h_r}{\beta'_*\,p/2} \qquad (B.4)$$

and the term R_0' is expressed as follows:

$$R_0' = \frac{h_\mathrm{r}}{(\lambda_\mathrm{t}\beta'_* \rho/2)^2\left[\frac{\varepsilon}{2-\varepsilon}Z + \frac{1}{\tanh(E\,d/2)}\sqrt{F\frac{\lambda_\mathrm{cd}}{\lambda_\mathrm{t}}}\right]} \tag{B.5}$$

$Z = 1$ applies for all materials except expanded polystyrene or insulating cork boards, see B.2.3, while E is a modified extinction parameter, due to coupled conduction and radiation heat transfer, expressed as:

$$E = \beta'_*\, p\,\sqrt{F\frac{\lambda_\mathrm{t}}{\lambda_\mathrm{cd}}} \tag{B.6}$$

The transfer factor, $\mathsf{T} = d/R$, often referred to in technical literature as measured, equivalent or effective thermal conductivity of a specimen, is expressed as follows if equation (B.1) is expressed as follows:

$$\mathsf{T} = \lambda_\mathrm{t}\ \frac{1}{1+\frac{\lambda_\mathrm{t}}{d}R_0'} \tag{B.7}$$

Both equation (B.5) and the term λ_cd may be written in different forms, depending on the material family.

B.2.2 Interpolating functions for wool-type products

B.2.2.1 One layer of homogeneous wool-type product

For wool-type products the parameter F that appears in equation (B.6) has values between 0,2 and 0,5; consequently the majority of the specimens have thicknesses such that $\tanh(E\,d/2)$ does not differ from 1 by more than 1%. In this situation the thermal resistance R_0', expressed by equation (B.5), becomes a thermal resistance R_0 independent of specimen thickness.

$$R_0 = \frac{h_\mathrm{r}}{\left(\lambda_\mathrm{t}\beta'_* \rho/2\right)^2\left[\frac{\varepsilon}{2-\varepsilon} + \sqrt{F\frac{\lambda_\mathrm{cd}}{\lambda_\mathrm{t}}}\right]} \tag{B.8}$$

The term λ_cd, which represents the combined conduction through the gaseous phase (air, of conductivity λ_a) and the solid matrix (of density ρ_s) of the insulating material, is expressed as:

$$\lambda_\mathrm{cd} = \lambda_\mathrm{a}\ \left(1 + B\,\rho/\left(1+\sqrt{\rho\rho_\mathrm{s}}\ B\right)\right) \tag{B.9}$$

where B is a constant parameter.

By introducing an additional parameter $C = 2\, h_r / \beta '_*$, and taking account of equations (B.4) and (B.9), equation (B.2) can be rewritten as follows:

$$\lambda_t = A\left(1 + B\,\rho / \left(1 + \sqrt{\rho \rho_s} B\right)\right) + \frac{C}{\rho} \quad \text{(B.10)}$$

Around room temperature, the thermal conductivity of air, λ_a can be expressed versus the Celsius temperature, θ, by the following expression:

$$\lambda_a = \lambda_{a0}\,(1 + 0{,}003052\,\theta - 1{,}282 \times 10^{-6}\,\theta^2) \qquad \text{(B.11)}$$

where λ_0 replaces the constant 0,0242396. Then equations (B.1), (B.2), (B.3), (B.4), (B.5) or (B.8) and (B.9) shall be used to interpolate experimental results. In these equations there are three material parameters that enter in the definition of the thermal transmissivity, namely the parameters A and B and the mass extinction parameter, $\beta '_*$. In addition the material bulk density and the mean test temperature shall be known. The definition of the thermal resistance or the transfer factor requires an additional material parameter, F (or its complement to 1, the albedo ω_*), and an additional testing condition, the emissivity, ε, of the apparatus.

B.2.2.2 One layer of mineral wool with uniform density gradient

There are situations when a wide density change exists in the direction of the specimen thickness. These changes are not rigorously linear, but the assumption

$$\rho = \rho_0\,(1 + k\,x) \qquad \text{(B.13)}$$

for the density in the direction x, parallel to the specimen thicknesses, is accurate enough for the purposes of this standard (k is a coefficient in the first order equation (B.13), while ρ_0 is the density for $x = 0$). The value $x = 0$ is in the centre of the specimen, so that the surfaces of a specimen of thickness d are at the coordinates $x = -d/2$ and $x = +d/2$.

When the thickness effect is not relevant, the integration of the Fourier's law between the coordinates x_1 and x_2, introducing equation (B.2) under the above assumptions, leads to the thermal resistance R_{12} of the layer of thickness $(x_1 - x_2)$:

$$R_{12} = \frac{x_1 - x_2}{\lambda_{cd}} - \frac{\lambda_r}{\lambda_{cd}^{\;2} k} \ln \left\{ \frac{1 + k x_1 \lambda_{cd} / \lambda_t}{1 + k x_2 \lambda_{cd} / \lambda_t} \right\} \qquad \text{(B.14)}$$

Equation (B.14) gives the thermal resistance R of the whole specimen when $x_1 = -d/2$ and $x_2 = +d/2$.

When the thickness effect is relevant, equation (B.1) becomes:

$$R = \frac{1}{2}\left(R_{01} + R_{02}\right) + R_{12} \qquad \text{(B.15)}$$

where R_{01} and R_{02} are computed from equation (B.8) by using the densities at the specimen surfaces of coordinates $-d/2$ and $+d/2$ respectively and R_{12} is the specimen thermal resistance given by equation (B.14).

B.2.3 Interpolating functions for cellular plastic materials and insulating cork boards

For almost all cellular plastic materials and insulating cork boards the parameter F that appears in equation (B.6) is close to zero, so that $\tanh(E\,d/2) = (E\,d/2)$, and the thermal resistance R_0', expressed by equation (B.5), still depends on the thickness d and becomes:

$$R_0^{'} = \frac{h_r}{\left(\lambda_{\mathrm{t}} \beta_*^{'} \rho / 2\right)^2 \left[\frac{\varepsilon}{2-\varepsilon} Z + \frac{2\lambda_{\mathrm{cd}}}{\beta_*^{'} d \ \rho \lambda_{\mathrm{t}}} \right]} \tag{B.16}$$

$Z = 1$ applies for all cellular plastics, except bead-board expanded polystyrene and insulating cork boards. For these materials Z is a function of specimen thickness and mean bead or grain diameter. The empirical expression $Z = 0{,}75 - 0{,}25 \tanh(d/3d_{\mathrm{b}})$, when d_{b} is the mean bead or grain diameter, has been found satisfactory.

The term λ_{cd}, which represents the combined conduction through the gaseous phase (of conductivity λ_{g}) and the solid matrix (of density ρ_{s}) of the insulating material, is expressed as:

$$\lambda_{\mathrm{cd}} = \lambda_{\mathrm{g}} \, (1 + B \, \rho) \tag{B.17}$$

where B is a constant parameter

For the radiativity, λ_{r}, again equation (B.4) is used.

By introducing the parameter $C = 2 \, h_{\mathrm{r}}/\beta'_*$, and taking account of equations (B.4) and (B.17), equation (B.2) can be rewritten as follows:

$$\lambda_{\mathrm{t}} = A(1 + B\rho) + \frac{C}{\rho} \tag{B.18}$$

Equations (B.1), (B.2), (B.3), (B.4), (B.16) and (B.17) shall be used to interpolate experimental results. In these equations there are three material parameters that enter in the definition of the thermal transmissivity, namely the parameters A and B and the mass extinction parameter, β'_*. In addition the material bulk density and the mean test temperature shall be known. The definition of the thermal resistance or the transfer factor requires an additional testing condition, the emissivity, ε, of the apparatus.

In principle any material parameter is temperature dependent. For some cellular plastics, as polystyrene foams, and for insulating cork boards the parameter β'_* is known to be temperature dependent. When the parameter β'_* is not a constant, a first order polynomial of temperature is satisfactory in most interpolations of measured data.

Annex C (informative)

Advanced procedures to test thick specimens exceeding thickness capabilities of the apparatus

C.1 Introductory considerations

The experimental procedure outlined in 5.3 is conceptually very simple but requires at least three measurements per specimen. Additionally, the procedure is not applicable to any specimen.

By accepting that thermal properties, material parameters and testing conditions may be linked in interpolating equations derived from heat transfer analysis through insulating materials, it is possible to cover almost any testing situation and to reduce the need for experimental data to a minimum. Some interpolating equations are valid for all insulating materials, see B.2.1 of annex B, while others apply to a restricted group of materials, see B.2.2 and B.2.3.

The procedures described in this annex can be grouped into the following categories:

a) preliminary procedures to assess whether the thickness effect is relevant, see C.2;

b) procedures applicable when the thickness effect is relevant, see C.3; these are further split into:

    1) preliminary procedures to derive needed material parameters when the thickness effect is relevant;

    2) routine procedures to assess the variation of product performance around its mean values; routine procedures are characterised by a limited number of measurements.

Preliminary measurements and evaluations are intended to define those material parameters that are common to one material family, one material, one product family or one product; some of these parameters may be fixed for a material in a product standard, or their measurement may be required for each product at the beginning of its production, considering the level of available information on parameter variability when a product standard is drafted.

Routine measurements and evaluations are intended to assess changes of product performance during production. They are indicated in product standards and are aimed at the determination of the parameters (usually just one) which can be regarded as having the greatest effect on changes of material performance.

Specific procedures are described for products that have density gradients along the thickness, see C.3.2.1.2 for mineral wool, or have the density increasing quite sharply towards both product surfaces (skin products), see C.3.2.2.3 for cellular-plastic skin-products.

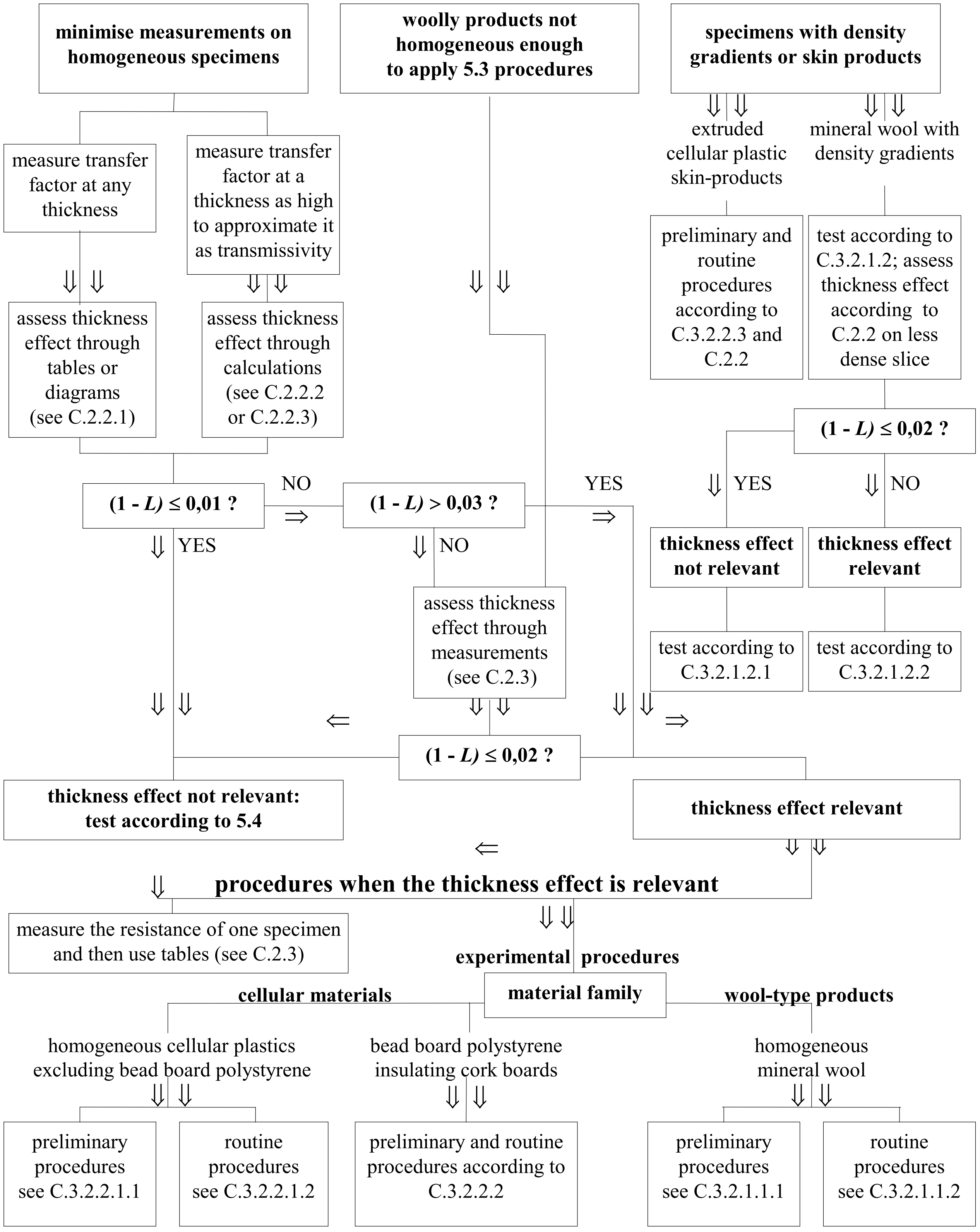


Figure C.1 - Advanced procedures to test thick specimens

C.2 Preliminary procedures on the relevance of the thickness effect

C.2.1 General

These procedures are divided into those requiring just one measured value and those based on an accurate set of measurements.

C.2.2 Preliminary estimation of the relevance of the thickness effect

Considering that testing accuracy is seldom better than 2 %, if not otherwise stated in a product standard, the thickness effect is not relevant when $1 - L \leq 0{,}02$.

When the tabulated values or the calculations described in C.2.2.2 at the minimum product thickness, d_m, are such that $R_0/(d_m/\lambda_t) \leq 0{,}01$, i.e. when $1 - L \leq 0{,}01$, no further experimental work is needed and the products are treated as purely conducting materials characterised by their thermal transmissivity λ_t, see 5.4.

When $0{,}01 < 1 - L < 0{,}03$ it is recommended to determine experimentally the actual relevance of the thickness effect, see C.2.3.

The preliminary estimations supplied in this clause assume equations (1) or (B.1) and equation (2) to be valid, as in 5.3, but assume additionally that R_o can be computed from the knowledge of some material parameters. Equation (B.8) is applicable to wool-type products and equation (B.16) for cellular plastic materials and insulating cork boards, see B.2 of annex B.

C.2.2.1 Assessment of the thickness effect through graphs or tables

For those materials enclosing air only in their solid matrix, it is possible to plot the ratio $L = \mathrm{T}/\lambda_t$, defining the thickness effect, as a function of the transfer factor and specimen parameters (thickness, extinction parameter and density).

> EXAMPLE From table 1, for a product 40 mm thick that has a transfer factor of 45 mW/(m·K) at 10 °C, the transfer factor lies between 0,970 and 0,973 of the thermal transmissivity; in other words the relevance of the thickness effect is approximately 3 % of the thermal transmissivity, i.e. is relevant.

C.2.2.2 Assessment of the thickness effect through calculations

A more accurate estimate of the thermal resistance R_0' can be obtained for the insulating materials containing air in their solid matrix if a measured value of the transfer factor at a relatively high thickness is available to be initially used as thermal transmissivity λ_t. Then, from equation (B.10) for wool-type materials, or equation (B.18) for cellular plastic materials and insulating cork boards, the contribution of conduction is deducted (see B.2.2 for wool-type materials and B.2.3 for cellular plastics and insulating cork boards) and hence the term C/ρ due to radiation heat transfer is available. Recalling that $h_r = 4\ \sigma_n\ T_m^3$,then

$$\rho\ \beta'_*/2 = h_r\ \rho/C$$

and hence all needed parameters to estimate R_0' are available.

> EXAMPLE A matt of mineral wool with a density of 11 kg/m³ has a thermal transmissivity of 0,045 W/(m·K) at 10 °C. The conductivity of the air is 0,0250 W/(m·K); then $B = 0{,}0015$ m³/kg, $B\ \rho = 0{,}0015 \times 11 = 0{,}0165$ and hence the conduction in the air and solid is given by $0{,}0250\ (1 + 0{,}0015 \times 11) = 0{,}0250 \times 1{,}0165 = 0{,}0254$. By difference, $C/\rho = 0{,}045 - 0{,}0254 = 0{,}0196$ W/(m·K). If an emissivity $\varepsilon = 0{,}92$ and $F = 0{,}5$ is assumed and $h_r = 4 \times 5{,}66997 \times 10^{-8} \times 283{,}15^3 = 5{,}149$ W/(m²·K) for 10 °C, then $\beta'_*\rho/2 = h_r\ \rho/C = 5{,}149/0{,}0196 = 262{,}9$ m⁻¹. Introducing the numerical data in equation (B.8) of B.2.2 leads to:

$$R_0 = \frac{5{,}149}{(0{,}045 \times 262{,}9)^2 \left[\frac{0{,}92}{2 - 0{,}92} + \sqrt{0{,}5 \frac{0{,}0254}{0{,}0450}} \right]} = 0{,}027\ \mathrm{m^2{\cdot}K/W}$$

For a minimum specimen thickness d_m = 50 mm it is then:

$$R_0/(d_m/\lambda_t) = 0{,}027/(0{,}050/0{,}045) = 0{,}024$$

i.e. R_0 is 2,4 % of the thermal resistance that would result from thermal transmissivity. The thickness effect is relevant and procedures outlined in C.3 should therefore be considered.

C.2.2.3 Special cases of the evaluation of the relevance of the thickness effect

For skin products (e.g. extruded polystyrene), the characteristics of the core material should be considered in a preliminary calculation of R_0'.

For mineral wool products with density gradients in the direction of thickness, the characteristics of an homogeneous material having the lowest density found in actual inhomogeneous product should be considered in a preliminary evaluation of the relevance of the thickness effect either by calculations of R_0 or through the use of table 1.

C.2.3 Procedures to measure R_0 and λ_t to assess the relevance of the thickness effect

The procedure of 5.3 can be applied with homogeneous specimens only. The following procedure averages most of the non-homogeneities normally encountered in insulating materials, thus supplying an accurate interpolation of thermal resistance at any thickness above d_∞. The procedure applies also to those products that are around the borderline for the relevance of the thickness effect and therefore require a reliable decision on further testing.

The following is an example of how the procedure could be followed for a single-specimen heat flow meter apparatus.

- Cut a set of three specimens, S1, S2 and S3, see figure C.2, having their thicknesses all equal to but not greater than one third of the maximum specimen thickness that can be accommodated in the test apparatus, e.g. from 30 mm to 50 mm.

- Test each of the specimens separately.

- Run three tests, at a thickness twice that of the single specimen, on the couples of specimens S1+S2, S2+S3 and S3+S1.

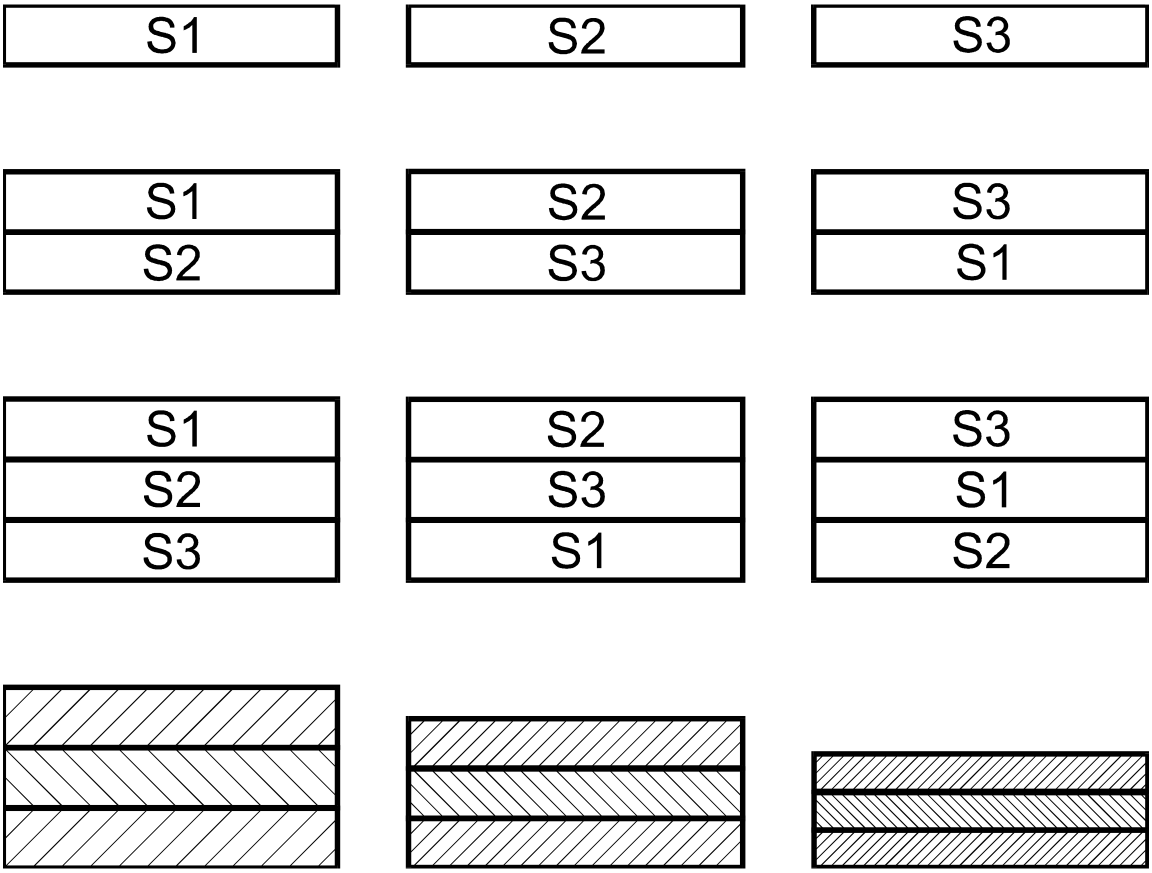
- Run three additional tests, at a thickness three times that of the single specimen, on the specimen stacks S1+S2+S3, S2+S3+S1 and S3+S1+S2.

- Compute the linear regression of the nine experimental data.

In this way the same weight is given to the data measured at each thickness, correctly averaging differences among specimens and then allowing the extrapolation to the full product thickness.

When a two-specimen guarded apparatus is used, two sets of three specimens are used.

Preliminary procedures for mineral wool having density gradients in the thickness direction are described together with those needed when the thickness effect is relevant in C.3.2.1.2.



The bottom row shows compressed stacks of three specimens of mineral wool

Figure C.2 - Special arrangements in the measurements on nearly homogeneous materials

C.3 Procedures when the thickness effect is relevant

C.3.1 Use of tabulated data when the thickness effect is relevant

When it has been ascertained, either from calculations or the experimental procedure of C.2.3, that the thickness effect is relevant (when $1 - L > 0,02$, if not otherwise stated in a product standard), previous testing experience on the same material should be used to decide whether the information supplied in tables 1 to 4 is accurate enough to run tests on one slice only and then extrapolate the transfer factor at the needed full specimen thickness.

In other cases, the following procedures can be used.

C.3.2 Experimental procedures when the thickness effect is relevant

The procedure here described assumes that the specimen thickness exceeds the apparatus capabilities, that the thickness effect has relevance and that the use of tables or calculations is not accurate within 1 % of the lowest expected thermal resistance for a specimen.

These procedures can also be used when the thickness effect is relevant but the maximum product thickness is still within the apparatus capabilities. In this case these procedures are used to derive material parameters and to avoid measurements at each product thickness.

C.3.2.1 Procedures for mineral wool

It is expected that when the thickness effect is relevant mineral wool products will have density gradients in the thickness direction; in this case see C.3.2.1.2. In case of homogeneous materials, the procedure described in C.3.2.1.1 can be used.

C.3.2.1.1 Procedures for homogeneous mineral wool

C.3.2.1.1.1 Preliminary procedure to derive material parameters

The purpose of this procedure is to limit the number of measurements required by only identifying those material parameters that are responsible for changes in product performance. Among these there is material density. It is therefore helpful to consider equation (B.10) or (B.18) and the related expression for λ_r given by equation (B.4). λ_t is split into three contributions: conduction in the air (A), conduction in the solid ($A\,B\,\rho/(1+\sqrt{\rho\,\rho_s}\;B)$) or $A\,B\,\rho$, and radiation (λ_r), the conduction in the solid and radiation being dependent on bulk density. For more details see B.2. Assuming that the value of A is known (e.g. through equation (B.11) for air), in principle at least two values of λ_t at one arbitrary mean test temperature at two different densities are needed to separate the parameters B and β'_*. In practice it is impossible to repeat the experimental procedure described in C.2.3 with additional groups of three specimens of the same material because their parameters B and β'_* would be different. The following procedure is an example of a procedure that solves this problem:

- Cut the product into as many specimens of equal thickness as those required to remain within the apparatus capabilities (e.g. a product of 300 mm is cut in three specimens of 100 mm).

- Test each individual specimen at its thickness and density.

- Stack specimens in a compressed state at three or four densities, e.g. to two-thirds, to one-third of the original total thickness and one or more intermediate thicknesses, see the bottom of figure C.1 of C.2.3.

  Tests are undertaken at different densities on the same material, according to equation (B.10), but what is determined in this case are values of the thermal resistance, R, given by equation (1) or transfer factor, T, given by equation (2) or (B.7) and not its limit value λ_t.

  Low compression rates, leading to densities not exceeding by more than 20 % the density of the non-compressed specimens may supply inaccurate interpolations; while high compression rates, leading to densities two or three times the density of the non-compressed specimens, may change the structure of the material. For advice on the maximum allowed compression rate, product standards can be consulted.

- Run the least squares analysis by using equation (1) of 5.2 together with equations (B.10) or (B.18) for thermal transmissivity and equation (B.8) (or (B.5) for very low density low thickness specimens) for R_0 as a function of material parameters. From the least square analysis, material parameters are derived.

  In equation (B.8) ε is the total hemispherical emissivity of the apparatus, β'_* a mass extinction parameter, ρ the bulk density of the material, while F and h_r are defined by equations (B.3). The parameter E appearing in equation (B.5) is a modified extinction parameter that can be expressed as in equation (B.6).

- Compute the specimen thermal resistance at the required thickness by using the interpolating equations and the material parameters derived through the least squares analysis.

  Of the material parameters, B is of little importance and F is not subject to great changes. So, A being known, material variability can be attributed to the parameter β'_* only. This means that for only a few specimens will the tests in the compressed state be required to get average parameters representative of the product (preliminary measurements and evaluations for type testing).

C.3.2.1.1.2 Routine procedure

As routine procedure it is suggested to test the product slices at their original density only. From these measurements the parameter β'_* is derived and then the full-thickness specimen thermal resistance is computed from equations (1) of 5.2 and B.8.

C.3.2.1.2 Procedures for mineral wool having density gradients in the thickness direction

The following is an example of a procedure for mineral wool having density gradients in the thickness direction.

- Cut the mineral wool product into a number of slices not exceeding the maximum allowed thickness for one apparatus and not less than one third of this thickness. (e.g. a specimen 240 mm thick is cut into three slices 80 mm thick).

  An odd number of slices is to be preferred because one slice corresponds to the centre of the specimen. The larger the slice thicknesses, up to the maximum allowed thickness for the apparatus, the lower the likelihood that the thickness effect is relevant for the slice. When the thickness effect is expected or known to be relevant, low slice thicknesses result in more accurate determination of some material parameters; in this case measurements on stacks of two or three slices should also be planned.

- Measure the density of each slice. Attribute the density of each slice at the coordinate corresponding to its centre, the origin of the coordinates being the centre of the specimen. Through the least square analysis, derive the parameters ρ_0 and k of equation (B.13), which correlates density with a coordinate x parallel to the specimen thickness.

  EXAMPLE A specimen 240 mm thick is cut into three slices 80 mm thick and the following densities are measured: 11,70 kg/m^3, 14,10 kg/m^3 and 20,30 kg/m^3. These densities are attributed to the coordinates -80 mm, 0 mm and +80 mm. The linear regression applied to equation (B.13) supplies the expression $\rho = 15{,}37(1 + 0{,}0538\ x)$ kg/m^3, where x is the coordinate expressed in millimetres.

- Compute the density at the two opposite surfaces $-d/2$ and $+d/2$ of the specimen. If they differ from the mean specimen density by less than 20 %, equation (B.14) differs by less than 1 % from the expression $R = d/\lambda_t$.

  EXAMPLE Referring to the specimen of the above example, at -120 mm it is $\rho = 8{,}92$ kg/m^3 and at +120 mm it is $\rho = 21{,}82$ kg/m^3; these values differ by 42 % from the mean specimen density, hence equation (B.14) shall be used.

- Measure the transfer factor of the least dense slice and compute the thermal resistance R_0 according to C.2.2.2 to make a preliminary decision on the relevance of the thickness effect related to the slices to be tested. Continue as indicated in C.3.2.1.2.1 or C.3.2.1.2.2 respectively if the thickness effect is not relevant or is relevant.

C.3.2.1.2.1 Procedures when the thickness effect is not relevant

The procedure can be continued as follows when the thickness effect is not relevant

- Measure the thermal resistance of the slice or the two slices in the centre of the specimen.
- Compute the solid and gaseous conductivity λ_{cd} as in C.2.2.2, using as density the mean specimen density (15,37 kg/m^3 in the above examples) and compute the thickness x_c in equation (B.13) that corresponds to the density of the slice having a density closer to the mean specimen density (in the above examples the central slice density 14,10 kg/m^3 corresponds to x_c = -23,6 mm). Compute the coordinates x_1 and x_2 that correspond to the slice centred on x_c. (in the above examples x_1 = -63,6 mm and x_2 = +16,4 mm). From equation (B.14), together with equations (B.2), (B.3) and (B.4) derive β'_* to be attributed to the specimen.
- Through the value of β'_* attributed to the specimen and equations (B.2) and (B.4), use equation (B.14) with $x_1 = -d/2$ and $x_2 = +d/2$ to compute the specimen thermal resistance.

  NOTE When $(k\,d/2) < 0{,}2$, the expression $R_{12} = (x_2 - x_1)/\lambda_t$ is used instead of equation (B.14).

Product standards can be consulted for advice on whether the above procedure is for both preliminary and routine use or for routine use only.

An accurate preliminary routine consists of the measurement of the thermal resistance of all the slices, in the determination of the appropriate coordinate corresponding to the slice density (see the second dash above) and in the determination of both λ_{cd} and β'_* by least square analysis of measured thermal resistances of the slices, expressed through equation (B.14), where the appropriate slice coordinates are introduced as in the second dash above.

C.3.2.1.2.2 Procedures when the thickness effect is relevant

When the thickness effect is relevant, the procedures outlined in C.3.2.1.2.1 are still valid, but equation (B.15) is then appropriate to compute both the specimen and slice thermal resistance. R_{01} and R_{02} are computed from equation (B.8) by using the densities at the specimen surfaces of coordinates $-d/2$ and $+d/2$ respectively or the densities at the slice surfaces x_1 and x_2. R_{12} is the specimen or slice thermal resistance given by equation (B.14). The parameter $F = 0{,}50$ can usually be applied in the calculation of R_{01} and R_{02}; in preliminary routines also F can be derived through the least squares analysis.

C.3.2.2 Procedures for cellular plastics and insulating cork boards

C.3.2.2.1 Procedures for homogeneous cellular plastics, excluding bead board polystyrene and insulating cork boards

When the evaluations of C.2 ask for further experimental determinations the following procedures can be used.

For many materials considered in this subclause, e.g. expanded polystyrene, specimen thicknesses fall also below d_∞.

C.3.2.2.1.1 Preliminary procedure

The following is an example of a preliminary procedure for homogeneous cellular plastics.

- Measure the thermal resistance of a slice of the product as thick as the maximum allowed specimen thickness for the apparatus.

- Reduce the slice thickness progressively by cutting away layers 10 mm to 20 mm thick; after each cut measure the thermal resistance of the remaining slice .

- Derive material parameters by the least squares analysis of measured thermal resistances.

For cellular plastic materials and insulating cork boards R_0' is represented by equation (B.16), copied here:

$$R_0' = \frac{h_r}{\left(\lambda_t \beta_*' \rho / 2\right)^2 \left[\frac{\varepsilon}{2-\varepsilon} Z + \frac{2\,\lambda_{cd}}{\beta_*' d\ \rho \lambda_t} \right]} \qquad \text{(B.16)}$$

$Z = 1$ applies for all cellular plastics, except bead board expanded polystyrene and insulating cork boards. By the least square analysis the parameters β'_*, A, B and F are computed (F tends to zero in most cases). When the material contains air, A is a fixed parameter given from equation (B.11).

C.3.2.2.1.2 Routine procedure

For routine testing, cut the product into slices as for homogeneous mineral wool, see C.3.2.1.1.1, derive the parameter β'_*, and from this and the parameters obtained by the preliminary procedure, compute R_0' and then the transfer factor of the product.

C.3.2.2.2 Procedures for expanded polystyrene bead boards and insulating cork boards

The procedure is the same as in C.3.2.2.1 but now A is the conductivity of the air, F tends to zero and Z is a function of specimen thickness and mean bead or grain diameter. The empirical expression $Z = 0{,}75 - 0{,}25 \tanh(d/(3d_b))$, when d_b is the mean bead or grain diameter, has been found satisfactory.

Unknown parameters to be derived by the least square analysis during the preliminary procedure are β'_*, B and the mean bead or grain diameter, d_b.

During the routine procedure consider β'_* only as an unknown parameter, as in C.3.2.1.1.2 for mineral wool and in C.3.2.2.1.2 for the remaining cellular plastics.

C.3.2.2.3 Procedures for extruded cellular-plastic skin-products

When the extrusion process of a cellular plastic material results in a product with much higher density at the surfaces of the product looking like a skin, the core material should be tested and the calculations of C.2.2.2 should be performed.

If calculations of C.2.2.2 indicate the need for more measurements, the following is a possible way of proceeding

- Determine the thermal resistance R_0' of the core material as for an homogeneous cellular material.

- Evaluate the product thermal resistance as the sum of the thermal resistances measured on each of the n layers, reduced by $(n - 1)$ times the thermal resistance R_0'. If during the cut some material is lost, make appropriate allowance for it in accordance with 5.4.

Annex D (informative)

Items which are expected to be specified in product standards

The clause number that proceeds each item in the following list indicates the clause of this standard where the item is quoted.

Subclause	**Item**
5.1	Product dependent specimen preparation
5.4	Procedures to compute the thermal resistance of a cut slice different from the one described in this standard
5.4	Option between the computation of the total thermal resistance of a specimen as the product of the thermal resistance of one slice and the number of equal slices composing the specimen or the computation as the sum of the measured thermal resistances of all the slices composing the specimen
5.5.1	When the thickness effect is relevant, determination of the thermal transmissivity of the material or the thermal resistance of the product
5.5.1	Use of tables 1 to 4 for the determination of the thermal transmissivity when the thickness effect is relevant
5.5.2	Selection of the interpolation procedure
5.5.3	Selection of the interpolation procedure
6	Information to be given in the test report
C.1	Material parameters to be fixed or measured in preliminary or routine procedures
C.2.2 And C.3.1	Relevance of the thickness effect when $1 - L > 0,02$, if not otherwise stated in a product standard
C.3.2.1.1.1	Maximum allowed compression rate when testing mineral wool products
C.3.2.1.2.1	Adoption of the procedure in C.3.2.1.2.1 both for preliminary and for routine use or for routine use only

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