SLOVENSKI STANDARD

SIST-TP CEN/TR 15131:2006

01-oktober-2006

Toplotne karakteristike gradbenih materialov ï Uporaba interpolacijskih enaļ b v odnosu do meritev toplote v tankih vzorcih ï Zaġļ itena vroļ a ploġļ a in merilniki toplotnih tokov

Thermal performance of building materials - The use of interpolating equations in relation to thermal measurement on thick specimens - Guarded hot plate and heat flow meter apparatus

Die Anwendung von Interpolationsgleichungen für wärmetechnische Messungen und dicken Probekörpern - Heizplatten und Wärmestrom-Messapparate

Performance thermique des matériaux pour le bâtiment - Utilisation des équations d'interpolation dans le cadre des mesurages thermiques sur éprouvette épaisse - Plaque chaude gardée et appareil a fluxmetre

Ta slovenski standard je istoveten z: CEN/TR 15131:2006

ICS:

91.100.60	Materiali za toplotno in zvoļ no izolacijo	Thermal and sound insulating materials
91.120.10	Toplotna izolacija stavb	Thermal insulation

SIST-TP CEN/TR 15131:2006 en

TECHNICAL REPORT

RAPPORT TECHNIQUE

TECHNISCHER BERICHT

CEN/TR 15131

January 2006

ICS 91.100.60; 91.120.10

English Version

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This Technical Report was approved by CEN on 27 September 2005. It has been drawn up by the Technical Committee CEN/TC 89.

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Ref. No. CEN/TR 15131:2006: E

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Foreword

This Technical Report (CEN/TR 15131:2006) has been prepared by Technical Committee CEN/TC 89 “Thermal performance of buildings and building components”, the secretariat of which is held by SIS.

1 Scope

This Technical Report supplements technical information on modelling of heat transfer in products of high and medium thermal resistance when the thickness effect may be relevant; by doing this it supplies minimum background information on the interpolating equations to be used in the procedures described in EN 12939 to test thick products of high and medium thermal resistance.

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.

Essential phenomena and common interpolating functions are presented in Clause 4, which is followed by separate equations for each material family.

This Technical Report also gives diagrams derived from the above interpolating equations to assess the relevance of the thickness effect for some insulating materials.

2 Normative references

The following referenced documents are indispensable for the application of this Technical Report. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 12939:2000, *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*

EN ISO 7345:1995, *Thermal insulation – Physical quantities and definitions (ISO 7345:1987)*

EN ISO 9288:1996, *Thermal insulation – Heat transfer by radiation – Physical quantities and definitions (ISO 9288:1989)*

3 Terms, definitions and symbols

For the purposes of this Technical Report, the terms and definitions given in EN ISO 7345:1995, EN ISO 9288:1996 and EN 12939:2000 apply.

NOTE EN ISO 9288 defines spectral directional extinction, absorption and scattering coefficients and the spectral directional albedo only, while this Technical Report makes use of total hemispherical coefficients, which can be obtained from the previous ones by appropriate integrations. To avoid confusion with the monochromatic directional coefficients, they are referenced here as related to the "two flux model", see Clause 4.

Symbol	Quantity	Unit
d	thickness	m
h	surface coefficient of heat transfer	
J	transfer factor	W/(m·K)
R	thermal resistance	m^2·K/W
T	thermodynamic temperature	K
ε	total hemispherical emissivity	
λ	thermal conductivity	W/(m·K)
λ_r	radiativity	
ρ	density	kg/m^3

σ	Stefan-Boltzmann's constant ($5,66997 \times 10^{-8}$)	$W/(m^2 \cdot K^4)$
θ	Celsius temperature	°C

4 Modelling thickness effect

4.1 General

The following qualitative description of heat transfer in low density homogeneous insulating materials formed the basis for the development of a model to get interpolating functions.

A graph of thermal resistance versus specimen thickness for all homogeneous insulating materials has the form of that in Figure 1. The extrapolation to zero thickness, R_0, of the straight portion (bold continuous line) depends both on material properties and testing conditions, in particular the emissivity of the surfaces bounding the specimen or product.

Only the slope of the straight portion of the plot of thermal resistance versus thickness is an intrinsic material property; the incremental ratio $\Delta d/\Delta R$ for $d > d_\infty$ is called thermal transmissivity, see EN ISO 9288.

Guarded hot plate or heat flow meter apparatus basically measure a thermal resistance, R. If the specimen thickness, d, is measured, then the transfer factor, $J = d/R$, can be calculated. The transfer factor is often referred to in technical literature as measured, equivalent or effective thermal conductivity of a specimen and, for low density insulating materials, depends not only on such material properties as the coefficient of radiation extinction, the thermal conductivity of the gas and solid matrix and air flow permeability but also on such testing or end-use conditions as product thickness, mean test temperature, temperature difference and emissivity of the bounding surfaces. When the specimen thickness is large enough, the transfer factor becomes independent of specimen thickness and emissivity of the surfaces of the apparatus, i.e. becomes a material property called thermal transmissivity.

NOTE 1 When different materials are considered, having the same thermal transmissivity, the same coefficient of radiation extinction and the same thermal conductivity of the gas and solid matrix, the thickness d_i, at which the straight portion of the plot starts, is larger for cellular plastic materials than for mineral wool. This is due to the different mechanism of the radiation extinction. Consequently for cellular plastic materials the thicknesses corresponding to the dashed portion of the plot, i.e. $d < d_i$, may more frequently than for mineral wool be larger than actual specimen thicknesses. For these reasons the procedures of this Technical Report should be differentiated by material families.

The following equations, describing the above phenomena, are those used in EN 12939 as interpolating tools.

NOTE 2 The model used assumes that all radiation beams crossing a plane in all possible directions can be grouped into those crossing the plane from its side A to the side B and those crossing the same plane from the side B to the side A, i.e. the radiation crossing the plane is reduced to a forward radiation intensity and a backward radiation intensity. This way of handling radiation is known as the "two-flux model". To radiation heat transfer, heat transfer by conduction was coupled.

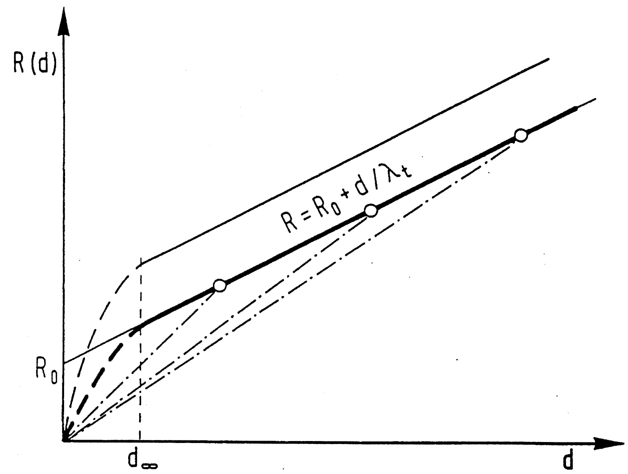
The thermal resistance, R, of a flat specimen of low-density material may be expressed as:

$$R = R'_0 + d/\lambda_t \tag{1}$$

where R_0' is not necessarily independent of the thickness d, and

$$\lambda_t = \lambda_{cd} + \lambda_r \tag{2}$$

According to EN ISO 9288 λ_t is the thermal transmissivity, λ_{cd} is the combined gaseous and solid thermal conductivity and λ_r is the radiativity. Possible expressions for the gaseous and solid conductivity, that are material-dependent, will be considered in the following subclauses.



The thickness d_∞ indicates the beginning of the straight portion of the plot of thermal resistance, R. A reduction of apparatus emissivity shifts the bold line upwards.

if $d < d_\infty$ The ratio of an increment in specimen thickness, Δd, to the corresponding increment in measured thermal resistance, ΔR, is not constant; the thermal transmissivity, λ_t, cannot be measured; the transfer factor, J, is not an intrinsic material property, as it depends on experimental conditions.

if $d > d_\infty$ The ratio $\Delta d/\Delta R$ is constant; the thermal transmissivity λ_t, that is an intrinsic material property independent of experimental conditions, can be measured. In this case, the radiativity λ_r and the gaseous and solid thermal conductivity λ_{cd} can also be defined as material properties and put $\lambda_t = \lambda_{cd} + \lambda_r$. Nevertheless $J = d/R$ is not yet independent of the thickness d, see dashed and dotted lines.

Figure 1 — Thermal resistance, R, as a function of the specimen thickness, d

If T_m is the mean test thermodynamic temperature, $\sigma_n = 5{,}66997 \times 10^{-8}$ W/(m²·K⁴) the Stefan-Boltzmann's constant, ε the total hemispherical emissivity of the apparatus, β_* a mass extinction parameter, ϖ_* an albedo, ρ the bulk density of the material, the following expressions are introduced:

$$F = (1 - \varpi_*^*) \qquad (3)$$

$$h_r = 4\,\sigma_n\,T_m^3 \qquad (4)$$

the radiativity, λ_r, is expressed as follows:

$$\lambda_r = \frac{h_r}{\beta_*' \cdot \frac{\rho}{2}} \qquad (5)$$

and the term R_0' is expressed as follows:

$$R_0' = \frac{h_r}{\left(\lambda_t \cdot \beta_*' \cdot \frac{\rho}{2}\right)^2 \left[\frac{\varepsilon}{2-\varepsilon} Z + \frac{1}{\tanh\left(E\,\frac{d}{2}\right)\sqrt{F\,\frac{\lambda_{cd}}{\lambda_t}}}\right]} \qquad (6)$$

$Z = 1$ for all materials except expanded polystyrene and insulating cork boards, see 4.3, while E is a modified extinction parameter, due to coupled conduction and radiation heat transfer, expressed as:

$$E = \beta_*^{'} \cdot \rho \sqrt{F \frac{\lambda_t}{\lambda_{cd}}} \qquad (7)$$

It becomes zero when the absorption parameter $\kappa_*^{'}$ is zero, i.e. the extinction parameter $\beta_*^{'}$ becomes simply the scattering parameter $\sigma_*^{'}$. E tends to infinity when conduction becomes negligible, i.e. when $\lambda_{cd} = 0$.

If the specimen thickness, d, is measured, the transfer factor can be calculated using Equation (1) as follows:

$$J = \lambda_t \frac{1}{1 + \frac{\lambda_t}{d} R_0^{'}} \qquad (8)$$

4.2 Interpolating functions for mineral wool and wood wool products

4.2.1 One layer of homogeneous mineral wool and wood wool product

For mineral wool and wood wool products the parameter F that appears in Equation (7) has values between 0,2 and 0,5, see [1] in the Bibliography. Consequently the majority of the specimens have thicknesses such that $(E\,d/2) > 3$, i.e. $\tanh(E\,d/2)$ does not differ from 1 by more than 1 %. In this situation the thermal resistance R_0', expressed by Equation (6), becomes a thermal resistance R_0 independent of specimen thickness.

$$R_0 = \frac{h_r}{\left(\lambda_t \cdot \beta_*^{'} \cdot \frac{\rho}{2}\right)^2 \left[\frac{\varepsilon}{2-\varepsilon} + \frac{1}{\sqrt{F \frac{\lambda_{cd}}{\lambda_t}}}\right]} \qquad (9)$$

Introducing two parameters A and B, the term λ_{cd}, that represents the combined conduction through the gaseous phase and the solid matrix (of density ρ_s) of the insulating material, is expressed as:

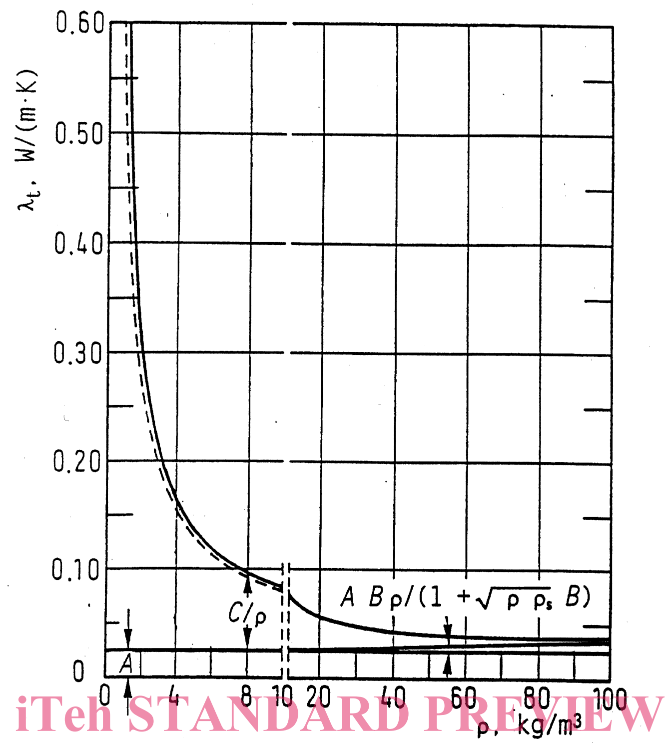
$$\lambda_{cd} = A\left(1 + \frac{B\rho}{1 + B\sqrt{\rho \cdot \rho_s}}\right) \qquad (10)$$

For glass wool products, B is close to 0,016 m^3/kg and ρ_s is close to 2400 kg/m^3. For the same products an even simpler expression is $\lambda_{cd} = A\,(1 + 0{,}0015\,\rho)$; this expression underestimates the conduction in the solid matrix at low densities, but for these densities this contribution is of minor importance.

When the density tends to zero, λ_{cd} approaches the thermal conductivity of the gaseous phase, represented in Equation (10) by the value of the parameter A.

By introducing an additional parameter $C = 2\frac{h_r}{\beta_*^{'}}$, and taking account of Equations (5) and (10), Equation (2) can be rewritten as in Equation (11), see its representation in Figure 2:

$$\lambda_T = A\left(1 + \frac{B\rho}{1 + B\sqrt{\rho \cdot \rho_s}}\right) + \frac{c}{\rho} \qquad (11)$$



The dashed line represents the transfer factor, J, of a layer of constant mass per area, $\rho\, d$.

Figure 2 — Thermal transmissivity λ_t and its components A, $A\, B\rho/(1+B\sqrt{\rho\rho_s})$ as a function of density, ρ, for a semi-transparent material (continuous line)

In the proposed model there are three material parameters that enter in the definition of the thermal transmissivity according to Equations (5) and (11), 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 material parameter, F (or its complement to 1, the albedo ω_*), and an additional testing condition, the emissivity, ε, of the apparatus.

In principle, any material parameter is temperature dependent. For mineral wool the effect of temperature on thermal resistance or transfer factor can be concentrated in the term h_r appearing in the radiativity and in the parameter A.

Around room temperature, the parameter A, i.e. the thermal conductivity of the air, can be expressed as a function of the Celsius temperature, θ, by the following expression:

$$\lambda_a = 0{,}0242396\ (1 + 0{,}003052\ \vartheta - 1{,}282 \times 10^{-6}\ \vartheta^2) \qquad (12)$$

To verify the proposed model, the expression within brackets in Equation (12) can be retained to express the correlation with temperature, while the constant 0,0242396 W/(m·K) can be replaced by an unknown, A_0, to be determined in the data regression to validate the model. Then, in general, the parameter A in Equation (11), as air is enclosed in the mineral wool and wood wool insulating materials, becomes:

$$A = A_0 (1 + 0{,}003052\ \vartheta - 1{,}282\ 10^{-6}\ \vartheta^2) \qquad (13)$$

Then Equations (1), (2), (3), (4), (5), (6) or (9), and (10) are used in EN 12939 to interpolate experimental results. Because Equation (12) represents the parameter A, the full characterisation of a mineral wool or wood wool product requires the determination of the parameter B, the mass extinction parameter β_*', and the albedo ω_* or its complement to unity, F. In addition any measurement shall be accompanied by the material density, ρ, the apparatus emissivity, ε, and the mean test temperature, T_m.

4.2.2 One layer of mineral wool with uniform density gradient

There are situations where there is a large density change in the direction of the specimen thickness. These changes are not rigorously linear, but the assumption

$$\rho = \rho_0 (1 + k \cdot x) \tag{14}$$

for the density in the direction x, parallel to the specimen thickness, is sufficiently accurate for the purposes of this Technical Report. The value $x = 0$ is at the centre of the specimen, so that the surfaces of a specimen of thickness d are at the coordinates $x = -d/2$ and $x = +d/2$. The thermal transmissivity of Equation (2) can still be defined at each distance x from the centre of the specimen; the gaseous and solid conductivity λ_{cd} is assumed independent of x and in Equation (10) the average specimen density is used, while Equation (14) is introduced in Equation (5) for the radiativity λ_r, and whenever it multiplies the extinction parameter β_*'.

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

$$R_{12} = \frac{(x_1 - x_2)}{\lambda_{cd}} - \frac{\lambda_r}{\lambda_{cd}^2 \, k} \ln\left[\frac{1 + (k x_1 \, \lambda_{cd} / \lambda_t)}{1 + (k x_2 \, \lambda_{cd} / \lambda_t)}\right] \tag{15}$$

Equation (15) 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 (1) becomes:

$$R = \frac{1}{2}(R_{01} + R_{02}) + R_{12} \tag{16}$$

where R_{01} and R_{02} are computed from Equation (9) 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 (15).

4.3 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 (7) is close to zero, so that tanh$(E\,d/2) = (E\,d/2)$ and the thermal resistance R_0', expressed by Equation (6), still depends on the thickness d and becomes:

$$R_0' = \frac{h_r}{(\lambda_t \cdot \beta_*' \cdot \rho / 2)^2 \left[\frac{\varepsilon}{2 - \varepsilon} Z + \frac{2\lambda_{cd}}{\beta_*' d \rho \lambda_t}\right]} \tag{17}$$

$Z = 1$ applies for all cellular plastics, except bead-board expanded polystyrene and insulating cork boards, which exhibit a different thickness effect due to the shielding effect of the skin of the beads or grains. For those materials Z is a function of specimen thickness and mean bead or grain diameter. The empirical expression $Z = 0{,}75 - 0{,}25 \tanh(d/3d_b)$, when d_b is the mean bead or grain diameter, has been found satisfactory.

Introducing two parameters A and B, the term λ_{cd}, that represents the combined conduction through the gaseous phase and the solid matrix (of density ρ_s) of the insulating material, is represented by the following relationship:

$$\lambda_{cd} = A(1 + B\rho) \qquad (18)$$

For cellular plastic materials, when B has little effect on the total λ_t and an approximate theoretical estimation is acceptable, it is suggested to put B = 0,4 $B = 0{,}4 \cdot \lambda_s / (\rho_s A)$ where λ_s and ρ_s are the conductivity and the density of the solid matrix of the insulation. The coefficient 0,4 depends upon the cell structure and can be adjusted for different cellular materials, the limiting values being 1/3 and 2/3. Table 1 gives, for some solid materials, the conductivity λ_s at 10 °C, the density ρ_s and the temperature coefficient F_T at 10 °C of the solid materials.

When the density tends to zero, λ_{cd} approaches the thermal conductivity of the gaseous phase, represented in Equation (18) by the value of the parameter A.

For the radiativity, λ_r, again Equation (4) is used.

By introducing the parameter $C = 2h_r / \beta_*'$, and taking account of Equations (5) and (18), Equation (2) can be rewritten as follows:

$$\lambda_t = A(1 + B \cdot \rho) + \frac{C}{\rho} \qquad (19)$$

Figure 2 is also an illustration of Equation (19).

Table 1 — Thermal properties of some solid materials

Material	Thermal conductivity λ W/(m·K)	Density ρ kg/m³	Temperature coefficient F_T %/K
Polystyrene	0,12	1050	0,34
Polyurethane	0,33	1250	0,27
Phenolic resin	0,28	1400	-
PVC	0,15	1200	-
Glass	1,0	2400	0,13

Table 2 — Thermal properties of some gases

Gas	Thermal conductivity λ W/(m·K)	Temperature coefficient F_T %/K
Air	0,0250	0,29
CO_2	0,015	0,47
CCl_3F (R11)	0,0077	0,57
CCl_2F_2 (R12)	0,0092	0,54

There are three material parameters that enter in the definition of the thermal transmissivity according to Equations (5) and (19), namely the parameters A and B and the mass extinction parameter, β_*'. In addition the material bulk density and the mean test temperature need to be known. The definition of the thermal resistance or the transfer factor involves also the emissivity, ε, of the apparatus.