

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

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National foreword

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English Version

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

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 à fluxmètre

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

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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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 ·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.

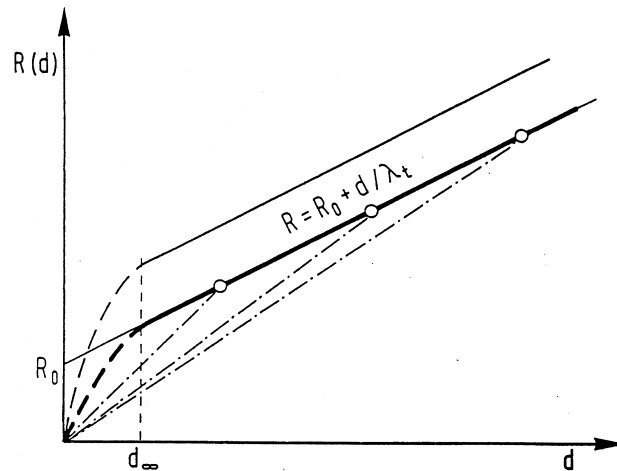
The thermal resistance, R , of a flat specimen of low-density material may be expressed as:

$$R = R'_0 + d/\lambda_t \quad (1)$$

where R'_0 is not necessarily independent of the thickness d , and

$$\lambda_t = \lambda_{cd} + \lambda_r \quad (2)$$

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, $\sigma_n = 5,66997 \times 10^{-8} \text{ W/(m}^2 \cdot \text{K}^4)$ 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:

$$F = (1 - \varpi^*) \quad (3)$$

$$h_r = 4 \sigma_n T_m^3 \quad (4)$$

the radiativity, λ_r , is expressed as follows:

$$\lambda_r = \frac{h_r}{\beta^* \cdot \frac{\rho}{2}} \quad (5)$$

and the term R_0' is expressed as follows:

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

$Z = 1$ 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:

$$E = \beta'_* \cdot \rho \sqrt{F \frac{\lambda_t}{\lambda_{cd}}} \quad (7)$$

It becomes zero when the absorption parameter κ'_* is zero, i.e. the extinction parameter β'_* becomes simply the scattering parameter σ'_* . 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:

$$J = \lambda_t \frac{1}{1 + \frac{\lambda_t}{d} R'_0} \quad (8)$$

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.

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

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:

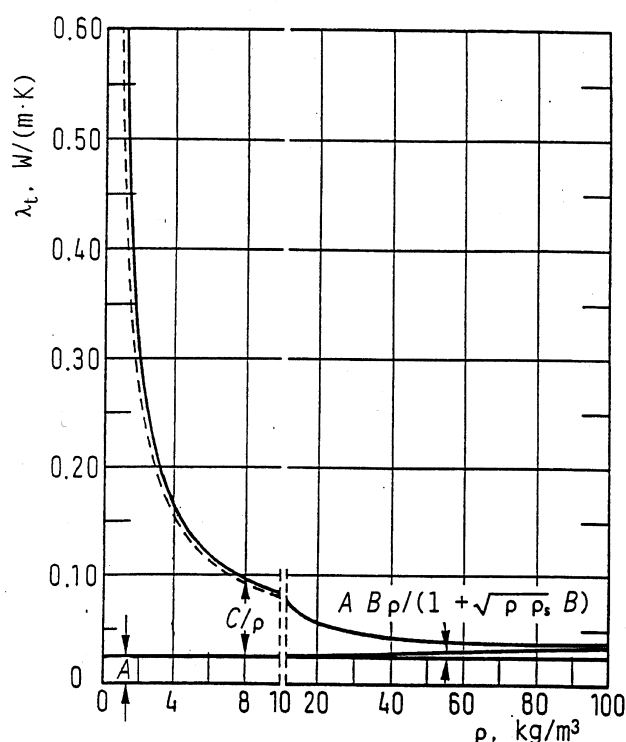
$$\lambda_{cd} = A \left(1 + \frac{B\rho}{1 + B\sqrt{\rho \cdot \rho_s}} \right) \quad (10)$$

For glass wool products, B is close to 0,016 m³/kg and ρ_s is close to 2400 kg/m³. 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:

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



The dashed line represents the transfer factor, J , of a layer of constant mass per area, ρd .

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'_s . 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_s), 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:

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

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:

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