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Thermal insulation — Moisture effects on heat transfer — Determination of thermal transmissivity of a moist material

Isolation thermique — Effets de l'humidité sur les propriétés relatives au transfert de chaleur — Détermination de la transmissivité thermique d'un matériau humide

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 10051 was prepared by Technical Committee ISO/TC 163, *Thermal insulation*, Subcommittee SC 1, *Test and measurement methods*.

Annexes A, B, C, D and E of this International Standard are for information only.

Introduction

The thermal transmissivity of a moist material is needed for the assessment of design values of thermal conductivity and thermal resistance under service conditions as described in ISO 10456[1]. The thermal transmissivity of a moist material is also necessary for any calculation of combined heat and moisture transfer. Heat transfer within moist porous materials involves a complex combination of

— radiation,

— conduction in the solid, liquid and gas phases,

— convection (in some operating conditions),

— mass transfer (in the moist materials),

and their interactions. While these heat and mass flow phenomena are transitory in nature, some of them have a long term contribution that must be recognised in the evaluation of thermal insulation performance. This International Standard determines the long-term contribution of both material structure and moisture on thermal transmissivity. This transmissivity, called thermal transmissivity of a moist material, is a material property and a function of the moisture content of the material. Normally, thermal transmissivity of a moist material varies locally in the material and is a function of the moisture content of each layer.

The correct operation of the apparatus used to obtain the thermal transmissivity of a moist material and the interpretation of experimental results are difficult tasks that require great care. It is recommended that the operator and the user of measured data both have a thorough background knowledge of heat and moisture transfer mechanisms in the materials, products and systems being evaluated, coupled with experience of measurements made using guarded hot plate or heat flow meter apparatus.

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Thermal insulation — Moisture effects on heat transfer — Determination of thermal transmissivity of a moist material

1 Scope

This International Standard specifies a method to determine the thermal transmissivity of a moist material (λ^*) under steady-state moisture conditions, i.e. not affected by moisture movement. It is measured using standardized guarded hot plate and heat flow meter methods, at temperatures above 0 °C. This material property is a function of the moisture content and does not represent the thermal performance of a material under service conditions. However, it can be used, together with knowledge of the moisture conditions in the material, to predict the practical thermal performance.

The use of λ^*, the distribution of moisture under service conditions and consequently the prediction of thermal performance under service conditions are outside the scope of this International Standard. However, the moisture distribution under service conditions should, where possible, be considered when λ^* is determined. Furthermore, transient methods of measurement are not included due to the difficulty involved in analysing and interpreting the results of these methods.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 7345:1987, *Thermal insulation — Physical quantities and definitions.*

ISO 9346:1987, *Thermal insulation — Mass transfer — Physical quantities and definitions.*

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.*

ISO 6946-1:1986, *Thermal insulation — Calculation methods — Part 1: Steady state thermal properties of building components and building elements.*

ISO 9288:1989, *Thermal insulation — Heat transfer by radiation — Physical quantities and definitions.*

ISO 10456:—[2], *Thermal insulation — Building materials and products — Determination of declared and design thermal values.*

3 Definitions

For the purposes of this International Standard, the following definitions apply.

3.1 thermal transmissivity of a moist material, λ^*: Intrinsic material property dependent upon moisture content and temperature but not on testing conditions. It is often referred to elsewhere as thermal conductivity of a moist material. It is defined for

2) To be published.

a moist material by the following differential equation during steady-state conditions:

$$q_m = -\lambda^{*} \cdot \frac{dT}{dx}$$

when moisture distribution within the material is in the steady-state and there is no liquid movement within the material.

NOTE 1 The transmissivity, either for dry materials (see ISO 9288, ISO 8301 and ISO 8302) or for moist materials (see this document) expresses a material property that has the dimension of a thermal conductivity but that can replace it only in some expressions (in most cases those related to steady-state heat and mass transfer in a slab). Usually transmissivity cannot replace conductivity in most two- and three-dimensional flow patterns, in the expression of thermal diffusivity and non steady-state problems. Due to the complexity of heat and mass transfer problems, transmissivity can seldom be determined through one single experiment, rather a procedure or particular testing conditions are required, e.g. tests at high thicknesses for the determination of the thermal transmissivity and equilibrium of moisture distribution and absence of moisture flow for the determination of thermal transmissivity of a moist material (non steady-state methods are usually excluded from the determination of transmissivity).

3.2 hygroscopic range: Moisture content in equilibrium with 98 % relative humidity or lower.

4 Symbols and units

For the purposes of this International Standard the following symbols and units apply.

Symbol	Quantity	Unit
a	Material-related constant in a linear relationship	$W \cdot m^2/(kg \cdot K)$
d	Thickness	m
g	Density of moisture flow rate	$kg/(m^2 \cdot s)$
g_t	Density of total moisture flow rate	$kg/(m^2 \cdot s)$
g_v	Density of vapour flow rate	$kg/(m^2 \cdot s)$
g_l	Density of liquid flow rate	$kg/(m^2 \cdot s)$
h	Specific enthalpy	J/kg
h_e	Specific latent enthalpy of evaporation or condensation	J/kg
h_v	Specific enthalpy of vapour	J/kg
h_l	Specific enthalpy of liquid	J/kg
q	Density of heat flow rate	W/m^2
q_m	Measured density of heat flow rate at the hot and cold sides of the specimen	W/m^2
R	Thermal resistance	$m^2 \cdot K/W$
t	Time	s
T	Thermodynamic temperature	K
v	Humidity by volume	kg/m^3
w	Moisture content mass by volume	kg/m^3
w_{cr}	Moisture content, below which g_l may be considered negligible	kg/m^3
w_v	Moisture content in vapour phase	kg/m^3
w_l	Moisture content in liquid phase	kg/m^3
δ_v	Moisture permeability	m^2/s
ρ	Bulk density of material	kg/m^3
λ	Thermal conductivity of dry material	$W/(m \cdot K)$
λ^{*}	Thermal transmissivity of a moist material	$W/(m \cdot K)$
ϕ	Relative humidity	

NOTE 2 In this International Standard, humidity by volume (v) has been used as the driving force for water vapour diffusion and moisture content mass by volume (w) as moisture content. The use of partial water vapour pressure (p_v) and moisture content mass by mass (u) respectively are equivalent provided that relevant material properties and boundary conditions are used.

Subscripts

b	Border between zones 1 and 2, see figure 2
cold	Cold surface of specimen
cr	See w_{cr}
hot	Hot surface of specimen
i	Arbitrary slice of specimen
l	Liquid
m	Measured
sat	Saturation
sur	Specimen surface
t	Total
v	Vapour

5 General considerations

5.1 Introduction

This clause describes the mechanisms by which moisture affects heat transfer in order to give the theoretical background for a test method which allows prediction of thermal performance in the presence of moisture.

Although the equations derived hereafter are as general as possible, examples of the use of these equations are given presupposing that measurements will be performed

— in standardized apparatus intended for a steady-state method (guarded hot plate or heat flow meter), and

— above freezing point.

5.2 Description of heat and mass transfers

Moisture flow is defined here to include flows of both vapour and liquid. Physically, moisture transfer is a combination of vapour and liquid flows in series and in parallel and it is normally not possible to clearly distinguish between the two kinds of flows. The specific enthalpy of vapour, however, differs considerably from that of liquid; it is therefore essential to treat moisture transfer as the sum of a vapour flow and a liquid flow:

$$g_t = g_v + g_l \qquad \dots (1)$$

In a closed system (i.e. with constant moisture content), steady-state moisture flow is reached when:

$$g_t = 0 \Leftrightarrow g_v = - g_l \qquad \dots (2)$$

In other words, steady-state moisture flow is reached when vapour and liquid transfers are equal and opposite, i.e. when movement of liquid by capillarity is balanced by movement of vapour by diffusion.

As vapour and liquid migrate, they carry their respective enthalpies, a condition which leads to an increase of heat transfer.

This heat transport caused by moisture flow is added to the conduction heat transfer described by Fourier's law, thus giving the following expression for the total density of heat flow rate, q:

$$q = - \lambda^{*} \cdot \frac{dT}{dx} + g_v \cdot h_v + g_l \cdot h_l \qquad \dots (3)$$

The first term in the right-hand part of equation (3) describes the heat flow caused by a temperature gradient. It consists essentially of

— conduction in the solid material and in the air in the pores of the material,

— conduction in water bound to the pore walls,

— evaporation and condensation within a pore or a local area, and

— thermal radiation and natural convection in the pores.

Each of these four heat flows is considered proportional to the gradient of temperature, so we can write by analogy with Fourier's law:

$$q = q_1 + q_2 + q_3 + q_4 = - \lambda^{*} \cdot \frac{dT}{dx} \qquad \dots (4)$$

In the case of thermal transmissivity of a moist material, increased conduction due to the presence of moisture in the material must be considered.

The second and third terms of equation (3) describe the parts of the heat flow associated with the enthalpies of vapour and liquid and the effects of evaporation and condensation. These fluxes are not proportional to the temperature gradient.

For the treatment of heat transfer in moist materials it is necessary to separate the mechanisms "conduction heat flux" and "heat flux by evaporation/diffusion/condensation".

In the past it has been customary to divide the total heat flux by the temperature gradient to obtain the thermal conductivity of a moist material. This procedure is clearly faulty, because it gives a variable value, dependent on conditions of measurement.

It is also important to distinguish carefully between moisture effects in service and those in laboratory test conditions.

Simulation of all the complex moisture effects, which occur under service conditions and during a test, is not considered within the framework of this document. Effects of moisture flow and phase changes depend entirely on the occurrence and magnitude of moisture transfer in the material. If these effects are allowed during the test, it is difficult to assess a material or component property. There will also be a great risk that these types of effects are estimated inaccurately. The main purpose of the test is therefore to determine λ^{*} which is a necessary basis for the prediction of the thermal performance in service conditions. The prediction itself is, however, outside the scope of this International Standard.

5.3 Determination of thermal transmissivity of a moist material

Determination of thermal transmissivity of a moist material requires a temperature gradient. Normally, a temperature gradient causes a redistribution of the moisture in the material, which leads to two types of problems:

— The test is carried out on material with changing and unknown moisture distribution.

— Redistribution of the moisture may simultaneously induce phase changes and heat transfer by moisture flow. Thus, heat is transported from the hot to the cold face by latent heat effects. However, by definition of the thermal transmissivity of a moist material according to this International Standard, such latent heat effects are not included. Therefore it is necessary to apply a correction to the measured heat flow (unless it is established that such a correction is zero or very small) before dividing by the temperature gradient.

During testing of a moist material the heat flow measured at the hot or cold surface will vary essentially as shown in figure 1: an initial phase A, with more or less constant heat flow due to the combined effect of conduction, effects of moisture flow and phase changes; a transition phase B, and finally phase C with moisture equilibrium.

Phase A is the period during the test, when the rate of evaporation at the hot face of the specimen is constant. This is only possible as long as the moisture content is above the hygroscopic range (relative humidity in the pores is approximately 100 %) and consequently the distribution of humidity by volume (or vapour pressure) is unaffected by changes in distribution of moisture content.

Phase A is deemed to occur if

— the moisture content at the hot face of the specimen is above the hygroscopic range, and

— the heat flow at the hot face of the specimen is constant for at least 2 h after thermal equilibrium has been reached.

During phase A there is evaporation of moisture at the hot face and vapour passes through the specimen. There is not an equal (counterbalancing) mass flow in the opposite direction in the liquid phase. Thus, there is net mass transfer and no moisture equilibrium.

In phase C, moisture evaporates at the hot face of the specimen, passes through the specimen in the vapour phase and condenses at the cold side. At the same time, water could be transferred in the liquid phase from the cold side to the hot side. In terms of mass, these two flows are equal and opposite, and there is equilibrium.

NOTE 3 Substantial moisture transfer in the liquid phase is very rare in thermal insulating materials and furthermore requires a moisture content above a critical level (w_{cr}).

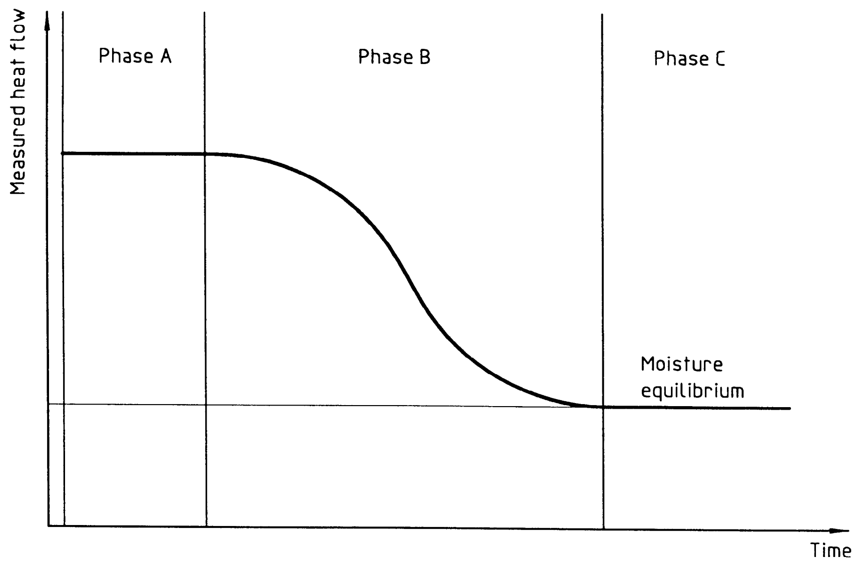

Figure 1 — Heat flow during a test to determine thermal transmissivity of a moist material

It can be derived [see annex A, equation (A.7)] that the measured heat flow at the hot and cold surfaces may be expressed as

$$q_m = \left(- \lambda^* \cdot \frac{dT}{dx} \right)_{sur} + (g_v \cdot h_e)_{sur} \qquad \ldots (5)$$

To determine $\lambda^*(w)$, the following must be known: the moisture content, the temperature gradient, the densities of heat flow and the moisture flow rates in the vapour phase at the surface.

6 Test apparatus

Heat flow meter apparatus according to ISO 8301 with two heat flux transducers (configuration b) is preferred. Heat flow meter apparatus (HFM) with one heat flux transducer at the hot side, or a guarded hot plate (GHP) according to ISO 8302 may also be used.

Downward vertical heat flow is recommended. If downward vertical heat flow is not used the risk of moisture redistribution by gravity air movements (convection) shall be considered.

Provision to record surface temperatures and heat flow(s) at the specimen's surface(s) as functions of time shall be made.

In some cases (see clause 7), additional temperature sensors to determine the temperature distribution within the test specimen shall be provided.

The test specimen shall be enclosed in a vapour-tight envelope, see 7.2 for details.

7 Test procedure

7.1 General

When carrying out tests on moist materials, the directions regarding test procedures for dry materials in the relevant International Standard for the apparatus shall be complied with.

Test temperatures shall not be high enough to damage the material. High temperatures may cause vapour pressures high enough to destroy the cell walls in closed-cell materials.

Further requirements for moist materials are given in 7.2. In case of discrepancies between this International Standard and the relevant International Standard for the apparatus, this International Standard takes precedence.

7.2 Specimen preparation and conditioning

The specimen shall be conditioned to the desired moisture content and moisture distribution.

Where possible, the moisture distribution under service conditions should be considered when λ^* is determined.

Conditioning may be by water immersion, with or without vacuum, absorption in humid air, spraying of water on the specimen or by subjecting the specimen to a temperature gradient. Combinations of these methods are also possible.

Note that, due to hysteresis effects, the moisture pre-history of the test specimen may influence the moisture content. The equilibrium moisture content at identical ambient conditions may depend on, for example, whether the equilibrium is reached by absorption or desorption.

Specimens having been conditioned under service conditions may also be tested.

The following guidance for conditioning in 7.2.1 and 7.2.2 covers most combinations of materials and moisture content levels.

7.2.1 Materials for which the effects of moisture movements may be neglected within the hygroscopic range

Condition the material at the desired relative humidity to constant mass. The moisture content may be considered uniform. Measure according to 7.4.1.1.

7.2.2 Materials for which the effects of moisture movements may be neglected above the hygroscopic range

Condition the specimen by subjecting it to a temperature gradient. Measure according to 7.4.1.

7.2.3 Other materials

Phase C is normally preferred. Condition the material under the same temperature gradient which is going to be used in the guarded hot plate or heat flow meter apparatus. Measure according to 7.4.2.

After conditioning the specimen it shall be enclosed in a vapour-tight envelope. The envelope shall prevent a change in moisture content greater than 0,01 kg/$(m^3 \cdot h)$.

If the presence of the envelope introduces significant thermal resistances between the specimen and the apparatus, the thermal resistance of the envelope