INTERNATIONAL STANDARD

ISO 15758

Second edition
2014-05-01

Hygrothermal performance of building equipment and industrial installations — Calculation of water vapour diffusion — Cold pipe insulation systems

Performance hygrothermique des équipements de bâtiments et installations industrielles — Calcul de la diffusion de vapeur d'eau — Systèmes d'isolation de tuyauteries froides

Reference number
ISO 15758:2014(E)

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Foreword

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The committee responsible for this document is ISO/TC 163, *Thermal performance and energy use in the built environment*, Subcommittee SC 2, *Calculation methods*.

This second edition cancels and replaces the first edition (ISO 15758:2004), which has been technically revised. The main changes are the following:

— in Clause 5, b), the alternative of using annual mean temperature and vapour pressure has been removed;

— the method of calculation given in 6.3 has been changed such that the total amount of condensation water in the whole pipe system is calculated based only on the outermost tangent to the saturation pressure, p_{sat};

— Figure 1 has been modified;

— the example given in A.3 has been changed;

— in Annex B, an explanation of the system with capacity for drying has been added;

— references have been added to the Bibliography.

Introduction

If the thermal insulation of a cold pipe system is not completely water vapour tight, there will be a flow of water vapour from the warm environment to the surface of the pipe, whenever the temperature of the surface of the cold pipe is below the dew point of the ambient air. This flow of water vapour leads to an interstitial condensation in the insulation layer and/or dew formation on the surface of the pipe itself. Interstitial condensation may cause the insulation material to deteriorate and dew formation on the surface of a metal pipe may cause corrosion over time. If the temperature is below 0 °C ice will be formed and the methods of this standard will not apply.

In period, when the dew point of the ambient air is higher than the temperature of the outer surface of the insulation, surface condensation will occur. This is dealt with in ISO 12241.

Different measures are available to control water vapour transfer and reduce the amount of condensation. The following are normally applied:

a) Installation of a vapour retarder;

b) Use of insulation materials with a high water vapour resistance factor (low permeability);

c) Use of a vapour retarder and a capillary active fabric to continuously remove condensed water from the pipe surface to the environment; see Annex B for an example.

Which protection measure is chosen depends on the ambient climate, the temperature of the medium in the pipe and the water vapour diffusion resistance of the insulation layer. The success of any system is strongly dependent on workmanship and maintenance. In any case anti-corrosion measures should be applied to a metal pipe in severe conditions.

The expected economic lifetime of an insulation system, assuming a maximum acceptable accumulated moisture content, can be calculated using the methods in this standard.

Hygrothermal performance of building equipment and industrial installations — Calculation of water vapour diffusion — Cold pipe insulation systems

1 Scope

This International Standard specifies a method for calculating the density of the water vapour flow rate in cold pipe insulation systems, and the total amount of water diffused into the insulation over time. The calculation method presupposes that water vapour can only migrate into the insulation system by diffusion, with no contribution from airflow. It also assumes the use of homogeneous, isotropic insulation materials so that the water vapour partial pressure is constant at all points equidistant from the axis of the pipe.

This International Standard is applicable when the temperature of the medium in the pipe is above 0 °C. It applies to pipes inside buildings as well as in the open air.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 9346, *Hygrothermal performance of buildings and building materials — Physical quantities for mass transfer — Vocabulary*

ISO 12241, *Thermal insulation for building equipment and industrial installations — Calculation rules*

ISO 12572, *Hygrothermal performance of building materials and products — Determination of water vapour transmission properties*

ISO 13788, *Hygrothermal performance of building components and building elements — Internal surface temperature to avoid critical surface humidity and interstitial condensation — Calculation methods*

3 Terms, definitions and symbols

For the purposes of this document, the terms and definitions given in ISO 9346, ISO 12572 and ISO 13788, and the following terms, definitions and symbols (see Table 1) apply.

3.1
exposed moist area
surface area of a capillary active fabric that is exposed to the ambient atmosphere

3.2
vapour retarder
material with high resistance to the flow of water vapour

3.3
corrected water vapour diffusion equivalent air layer thickness
thickness of an imaginary plane layer with μ =1, and an area of πD_j which has the same diffusion resistance as the layer j with $\mu = \mu_j$

Note 1 to entry: See Formula (18).

Table 1 — Symbols and associated units

Symbol	Quantity	Unit[a]
A'_e	Surface area from which evaporation takes place per linear metre of the pipe	m^2/m
D_0	Outside diameter of cold pipe	m
D_j	Outside diameter of *j*-th layer of an insulation system	m
D_n	Outside diameter of the outer layer of an insulation system	m
G	Total moisture uptake over a period per linear metre of pipe [refer to Formula (2)]	kg/m
G'	Total moisture uptake over a period per linear metre of pipe	kg/m
P	Actual atmospheric pressure	Pa
P_0	Standard atmospheric pressure = 101 325	Pa
R_v	Gas constant for water vapour = 461,5	J/(kg·K)
T	Thermodynamic temperature	K
Z'_{fl}	Water vapour resistance of one thin foil, cladding or skin per linear metre of pipe	m·s·Pa/kg
Z'_j	Water vapour resistance of *j*-th layer of an insulation system per linear metre of pipe	m·s·Pa/kg
Z'_P	Water vapour resistance of insulation system per linear metre of pipe	m·s·Pa/kg
d	Thickness of an insulation layer	m
f_e	Evaporation factor	$kg/(m^2·s·Pa)$
g'	Water vapour flow rate within the insulation per linear metre of pipe	kg/(m·s)
g'_c	Rate of condensation per linear metre of pipe	kg/(m·s)
g'_e	Evaporation rate per linear metre of pipe	kg/(m·s)
h_c	Convection heat transfer coefficient	$W/(m^2·K)$
p	Partial water vapour pressure	Pa
p_a	Partial water vapour pressure of air	Pa
p_{sat}	Saturated water vapour pressure	Pa
s_d	Water vapour diffusion equivalent air layer thickness	m
s_{df}	Water vapour diffusion equivalent air layer thickness of foils	m
t	Period of calculation (month or year)	Month, year
x	Distance	m
δ	Water vapour permeability	kg/(m·s·Pa)
δ_0	Water vapour permeability of air	kg/(m·s·Pa)
$\sigma_{d,j}$	Corrected water vapour diffusion equivalent air layer thickness of layer *j*	m
$\tilde{\sigma}_{d,j}$	Total corrected water vapour diffusion equivalent air layer thickness from surface of cold pipe to the outside of layer *j*	m
μ	Water vapour resistance factor	—
θ_0	Temperature of the medium in the pipe	°C

[a] For practical reasons, hours or days are often used instead of seconds as units of time.

4 Calculation formulae

4.1 General

The density of water vapour flow rate, g, through a material is calculated by the following formula:

$$g = -\delta \frac{\mathrm{d}p}{\mathrm{d}x} \tag{1}$$

where δ is the water vapour permeability of the material.

The total moisture uptake during a period, G, is given by

$$G = \int_0^t g \, \mathrm{d}t \tag{2}$$

In calculations the diffusion resistance factor, μ, is commonly used instead of the permeability:

$$\mu = \frac{\delta_0}{\delta} \tag{3}$$

where δ_0 is the water vapour permeability of still air, which can be calculated from

$$\delta_0 = \frac{0{,}083 P_0}{R_V \cdot T \cdot P} \cdot \left(\frac{T}{273} \right)^{1{,}81} \tag{4}$$

For approximate calculations, δ_0 can be assumed to be constant in the temperature range under consideration; the following value can therefore be used:

$$\delta_0 = 2{,}0 \times 10^{-10} \tag{5}$$

4.2 Homogeneous insulation

In the case of a cold pipe with a single homogeneous layer of insulation, the density of water vapour flow per metre of an insulated cold pipe is given by replacing the differential expression by the vapour pressure difference in Formula (1):

$$g' = \frac{p_\mathrm{a} - p_\mathrm{sat}(\theta_0)}{Z'_\mathrm{P}} \tag{6}$$

where

p_a is the vapour pressure of the ambient air, in Pa;

$p_\mathrm{sat}(\theta_0)$ is the saturation vapour pressure at the outside surface of the pipe, in Pa;

Z'_P is the water vapour resistance per linear metre of the pipe insulation, in m·s·Pa/kg, defined by Formula (7):

$$Z'_\mathrm{P} = \frac{\ln\left(\frac{D_1}{D_0} \right)}{2 \pi \delta} \tag{7}$$

If the actual vapour pressure, p, does not cross the saturation pressure, p_sat, condensation occurs only at the surface of the cold pipe. When the actual vapour pressure crosses the saturation vapour pressure, follow the procedure described in Clause 6.

The total water uptake over a period t is then given by

$$G' = \int_0^t \frac{p_a(t) - p_{sat}\left[\theta_0(t)\right]}{Z'_P} dt \tag{8}$$

4.3 Multi-layer insulation systems

The water vapour resistance, Z'_P, of an insulation system with n different layers is given by

$$Z'_P = \sum_{j=1}^{n} \frac{\ln\left(\frac{D_j}{D_{j-1}}\right)}{2\pi\delta_j} \tag{9}$$

which gives

$$Z'_P = \frac{1}{2\pi\delta_0} \sum_{j=1}^{n} \mu_j \ln\left(\frac{D_j}{D_{j-1}}\right) \tag{10}$$

where

$$\mu_j = \frac{\delta_0}{\delta_j}$$

j = 1 to n defines the layers from the cold pipe outwards.

Formula (10) can be an approximate means of calculating water vapour resistance of a homogeneous insulation material with water vapour resistance highly dependent on temperature.

NOTE See the example given in A.2.

If the outer layer, n, is a vapour retarder jacket, foil or skin, with negligible thickness, but with large water vapour diffusion-equivalent air layer thickness, s_{df}, the water vapour resistance of the retarder will be

$$Z'_n = \frac{1}{\pi\,\delta_0\,D_n} s_{df} = \frac{1}{2\,\pi\,\delta_0} \frac{2s_{df}}{D_n} \tag{11}$$

The water vapour resistance of the whole system is then

$$Z'_P = \frac{1}{2\pi\delta_0}\left[\sum_{j=1}^{n-1} \mu_j \ln\left(\frac{D_j}{D_{j-1}}\right) + \frac{2s_{df}}{D_n}\right] \tag{12}$$

The total water uptake over a period t is then given by Formula (8).

4.4 Systems with capacity for drying

For cold pipe systems with drying-out capacities the total water uptake G' in the system is given by

$$G' = \int_0^t (g' - g'_e) dt \tag{13}$$

where g'_e is the drying capacity per linear metre of pipe, in kg/(m·s).

For insulation systems, where the drying capacity is obtained by utilizing the wicking action of a capillary active fabric, the capacity is determined by the evaporation from the freely exposed moist area of the fabric per metre length of pipe, A'_e:

$$g'_e = f_e \left(p_{sat}(\theta_a) - p_a \right) A'_e \tag{14}$$

where $p_{sat}(\theta_a)$ is the saturation vapour pressure at the ambient temperature, in Pa.

The evaporation factor, f_e, can be determined by measurement or calculation:

$$f_e = \frac{h_c}{R_v T \rho c_p} \tag{15}$$

where

h_c is the convection heat transfer coefficient, in W/(m²·K);

R_v is the gas constant for water vapour = 461,5 J/(kg·K);

ρ is the density of air = 1,205 kg/m³ at 20 °C;

c_p is the specific heat capacity at constant pressure of air = 1 005 J/(kg·K) at 20 °C.

NOTE A method of measurement is given in B.2. Formula (14) is an approximate expression because the wick temperature is not equal to the ambient temperature due to the evaporation. Further information regarding Formula (15) is to be found in Reference[5] in the Bibliography.

For horizontal and vertical pipes in still air h_c = 10 W/(m²·K), giving $f_e = 6 \times 10^{-8}$ kg/(m²·s·Pa).

The total water uptake over a time, t, is then given by

$$G' = \int_0^t \left[\frac{p_a - p_{sat}(\theta_0)}{Z'_P} - f_e\left(p_{sat}(\theta_a) - p_a\right) A'_e \right] \mathrm{d}t \tag{16}$$

5 Boundary conditions

The following boundary conditions for temperature and vapour pressure shall be used to evaluate the formulae given in Clause 4.

a) **At surface of cold pipe**

The surface temperature of the cold pipe shall be taken as the temperature of the medium in the pipe. The vapour pressure at the surface shall be taken as the saturated vapour pressure at that temperature, i.e. a relative humidity of 1,0.

b) **Ambient air**

Outside buildings, use the monthly mean temperature and vapour pressure of the warmest month.

Inside buildings, use the temperature and vapour pressure representative of the use of the building in the warmest month of the year. Methods for deriving internal conditions are given in ISO 13788.

NOTE Use of the monthly mean vapour pressure gives results which are on the safe side.

6 Calculation procedure

6.1 General

The formulae given in Clause 4 allow the calculation of the total amount of water condensing within the cold pipe insulation and determination of whether condensation occurs within the insulation material or only on the pipe surface.

For the evaluation of the amount of water vapour transported into an insulated cold pipe system the following procedures shall be followed step by step.

6.2 Calculation of rate of condensation in single homogenous insulation layer

a) Define the service temperature of the cooling medium and the temperature and relative humidity of the environment.

b) Determine the vapour pressure corresponding to the given climatic conditions.

c) Calculate the amount of water uptake using Formula (8).

6.3 Calculation of rate of condensation in multi-layer insulation system

a) Define the service temperature of the cooling medium and the temperature and relative humidity of the environment.

b) Calculate the temperature distribution through the insulation in accordance with ISO 12241.

c) Calculate the saturation pressure distribution as a function of temperature in accordance with ISO 13788.

d) Calculate the value of the corrected water vapour diffusion equivalent air layer thickness, $\sigma_{d,j}$, for the boundaries between each layer j of the insulation. $\sigma_{d,j}$ is defined as the thickness of an imaginary plane layer with $\mu = 1$, and an area of πD_j which has the same diffusion resistance as the layer j with $\mu = \mu_j$:

$$\frac{\sigma_{d,j}}{\delta_0 \pi D_j} = \frac{\ln\left(\frac{D_j}{D_{j-1}}\right)}{2\pi\delta_0 / \mu_j} \tag{17}$$

which gives

$$\sigma_{d,j} = \mu_j \frac{D_j}{2} \ln\left(\frac{D_j}{D_{j-1}}\right) \tag{18}$$

e) Calculate the total corrected water vapour diffusion equivalent air layer thickness, $\tilde{\sigma}_{d,j}$, from the outside surface of the cold pipe to each interface between materials:

$$\tilde{\sigma}_{d,j} = \sum_{i=1}^{j} \sigma_{d,i} \tag{19}$$

f) Draw the saturated vapour pressure as a function of $\tilde{\sigma}_{d,j}$, for each layer of cold pipe system elements.

Then draw the actual vapour pressure profile as a straight line between the vapour pressure of the environment and that at the outer surface of the pipe.

1) If the actual vapour pressure p does not cross the saturation pressure p_{sat}, condensation will occur only on the outer surface of the pipe. The condensation rate is then given by Formula (6).

2) If p crosses p_{sat} then condensation will occur within the insulation material. Determine the tangent to the outermost condensation point and calculate the condensation rate in the insulation material and at the pipe surface from

$$g'_{c} = \delta_0 \left(\frac{p_a - p_{sat}(\theta_c)}{\tilde{\sigma}_{d,T} - \tilde{\sigma}_{d,c}} \right) \tag{20}$$

where

θ_c is the temperature at the interface where the condensation is occurring, in °C;

$\tilde{\sigma}_{d,c}$ is the sum of the $\sigma_{d,j}$ values from the pipe to the interface between materials where condensation is occurring;

$\tilde{\sigma}_{d,T}$ is the sum of the $\sigma_{d,j}$ values from the pipe to outside of the insulation.

The condensation rate at the pipe surface can be approximately calculated as the product of the saturated vapour pressure gradient and the water vapour permeability. However the precision of this value should be regarded as low, since the liquid movement is not taken into account.

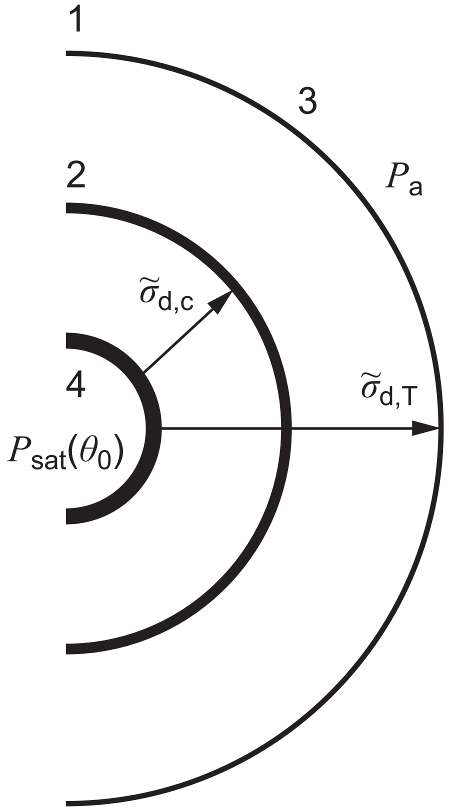
g) If the water vapour resistance factor of an insulation material is strongly temperature dependent, the insulation layer should be divided into sub layers with different water vapour resistance factors.

NOTE An example of the calculation is given in A.2.

h) Calculate the total accumulation on the pipe and in the insulation system by integrating the individual condensation rates over time:

$$G' = \int_0^t g'_c(t)\,dt \tag{21}$$

See Figure 1.



Key

1 outside surface of insulation system

2 condensation interface

3 ambient air

4 cold pipe

Figure 1 — Cross-section of insulated cold pipe with condensation interface within the insulation system

Annex A
(informative)

Examples

A.1 Water uptake in insulated cold pipe with vapour retarder on outside

Water vapour resistance factor of the insulation μ_1 = 50;

Insulation thickness d_1 = 0,05 m;

Pipe diameter without insulation D_0 = 0,1 m;

Water vapour equivalent air layer thickness of vapour retarder s_{df} = 100 m;

Climatic conditions:

— ambient temperature 20 °C, relative humidity 0,7, giving p_a = 1 636 Pa;

— pipe medium temperature 5 °C, giving $p_{sat}(\theta_0)$ = 872 Pa.

The vapour resistance of the whole insulation system is given as per Formula (12):

$$Z'_P = \frac{1}{2\pi \times 2\times 10^{-10}} \left[50 \times \ln\left(\frac{0,2}{0,1}\right) + \frac{2\times 100}{0,2} \right] = 8,23\times 10^{11} \quad \text{m·Pa·s/kg} \tag{A.1}$$

The density of water vapour flow rate is given as per Formula (6):

$$g' = \frac{1\,636 - 872}{8,23\times 10^{11}} = 9,28\times 10^{-10} \quad \text{kg/(m·s)} \tag{A.2}$$

The mass accumulated over a year is G' = 0,029 kg/m.

A.2 Cold pipe insulated with one layer of material with highly temperature-dependent water vapour resistance factor

In this example it is assumed that a cold pipe is insulated by a 30 mm thick material with a water vapour resistance factor that varies linearly from 2 000 at 0 °C to 500 at 25 °C. This is treated as three layers of equal thickness with resistance factors of 1 750, 1 250, and 750.

Pipe diameter without insulation: D_0 = 0,088 m;

Insulation layer 1:	μ_1 = 1 750,	d_1 = 0,010 m,	D_1 = 0,108 m;
Insulation layer 2:	μ_2 = 1 250,	d_2 = 0,010 m,	D_2 = 0,128 m;
Insulation layer 3:	μ_3 = 750,	d_3 = 0,010 m,	D_3 = 0,148 m;

Climatic conditions:

— ambient temperature 25 °C, relative humidity 0,7, giving p_a = 2 216 Pa;

— pipe medium temperature 0 °C, giving $p_{sat}(\theta_0)$ = 611 Pa.

The total water vapour resistance is given by Formula (10) as:

$$Z'_{\mathrm{P}} = \frac{1}{2\pi \times 2 \times 10^{-10}} \left(1\,750 \times \ln\left(\frac{0{,}108}{0{,}088}\right) + 1\,250 \times \ln\left(\frac{0{,}128}{0{,}108}\right) + 750 \times \ln\left(\frac{0{,}148}{0{,}128}\right) \right) \quad \text{(A.3)}$$

$$= 5{,}41 \times 10^{11} \quad \mathrm{m \cdot Pa \cdot s/kg}$$

The density of water vapour flow rate is then calculated from Formula (6) as:

$$g' = \frac{(2\,216 - 611)}{5{,}41 \times 10^{11}} = 2{,}97 \times 10^{-9} \ \ \mathrm{kg/(m \cdot s)} \quad \text{(A.4)}$$

The mass accumulated over a year is G' = 0,0845 kg/m.

A.3 Example of calculation when actual vapour pressure p crosses saturation pressure p_{sat}

In this example, the condensation rate is calculated when the actual vapour pressure crosses the saturation pressure.

Determine the tangent to the outermost condensation point and calculate the condensation rate in the insulation material and at the pipe surface from: The condensation rate in the whole pipe system can be calculated as the product of the saturated vapour pressure gradient at the outermost condensation point and the water vapour permeability.

Annex B
(informative)

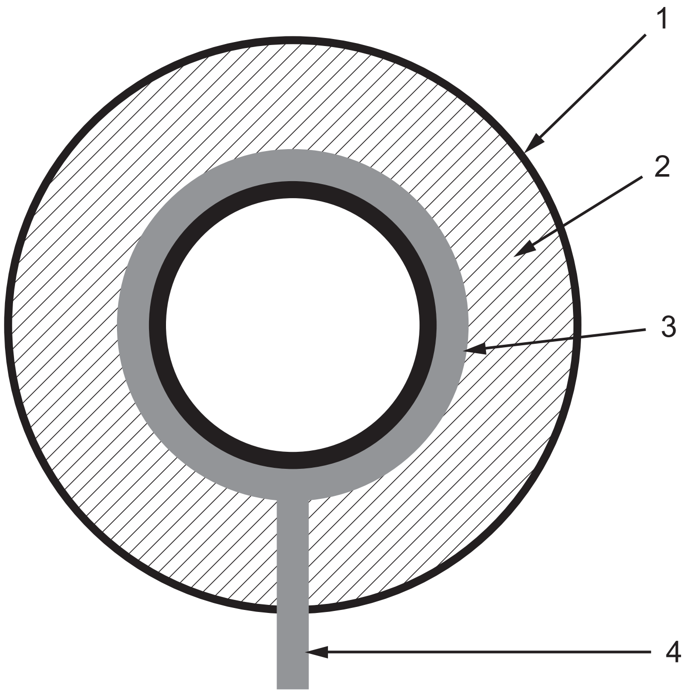
System with capacity for drying and experimental determination of evaporation rate from surface of wet wick fabric

B.1 System with capacity for drying

As an alternate to the traditional approach, a method to remove condensed water from the system utilizing wicking material has been in use.[4][10][11] The approach accepts the fact that water vapour will enter the system and condense on the cold surface and provides a means to remove it from the system while keeping the insulation material substantially dry.[3][12]-[15]

A typical application of wicking technology is shown in Figure B.1. A thin layer of hydrophilic wicking material is placed around the pipe. A layer of low conductivity insulation material is located around the wick to limit conduction heat transfer to the pipe. A vapour retarder is placed on the exterior surface of the insulation to limit the rate of water vapour diffusion into the system. The wicking material is extended downward through a slot in the insulation layer, and the tail of the wick is left exposed to the ambient air to serve as an evaporator section. Although the evaporator section of the wick is shown hanging straight down in a vertical position, this tail portion of the wick may be turned and adhered to the exterior of the vapour retarder in practice.

Any liquid water that condenses on the pipe surface is absorbed by the wicking material and transported via the combination of capillary forces and gravity through the slot and onto the exposed trail area where it can evaporate to the ambient air.



Key

1 vapour retarder

2 insulation

3 wicking material around pipe

4 evaporator region of wick

Figure B.1 — Schematic of system

B.2 Experimental determination of evaporation rate from surface of wet wick fabric

B.2.1 Principle

A wet specimen of the wick fabric is placed on a horizontal underlay of plastic foam within a controlled temperature and humidity environment. Because of the difference between the partial water vapour pressure at the wet surface of the wick fabric and in the atmosphere, water vapour will evaporate into the atmosphere. The test assembly is weighed periodically to determine the rate of evaporation.

B.2.2 Apparatus

The apparatus consists of the following equipment:

a) chamber capable of being maintained at a specific relative humidity within the range of relative humidity from 0,5 to 0,7, to an accuracy of ± 0,02 relative humidity and a specific temperature within the range of 20 °C to 25 °C to an accuracy of ± 1 °C;

b) balance capable of weighing the test assembly to an accuracy of 0,01 g;

c) test assembly as shown in Figure B.2;

d) two jars of equal size with screw caps are placed on a tray and fixed at a distance of approximately 100 mm by means of a shaped piece of plastic foam of thickness equal to the height of the jars including the lids.

A slit is cut in each lid with width a little larger than the thickness of the fabric to be tested and a length of 50 mm. The fabric test specimen has a width of 50 mm and length equal to the distance between the slots plus 100 mm.

The test specimen is placed on the plastic foam plate to produce conditions similar to those in practice when the fabric wick strips are taped to the pipe insulation. This means that the latent heat of evaporation comes only from the ambient air. To obtain a conservative measurement of the evaporation rate in still air, the test assembly should be shielded from draughts.

B.2.3 Procedure

The tray with the two jars is placed horizontally on a table and the two jars filled with distilled water up to a few mm of the brim; the lids are screwed down. The ends of the fabric test strip are pushed down through the slot in each jar so that approximately 50 mm of the strip is in the water in each jar. Self-adhesive tape is placed over the slots and parts of the strip so that the free exposed length of the test strip is 100 mm.

After the test strip has become wet due to the capillary suction properties of the wick fabric, it is pressed down onto the plastic foam underlay, so that evaporation only takes place from the top. The tray, with the test assembly, is then weighed at regular intervals of approximately 1 hour.

B.2.4 Calculation

The mass of the assembly is plotted against time, and the evaporation rate is determined from the slope, α in g/s, of the regression line derived from at least eight readings. The evaporation factor, f_e, is calculated from:

$$f_e = \frac{\alpha}{3{,}6 \times 10^6 \left(p_{sat}(\theta_a) - p_a \right) A} \tag{B.1}$$

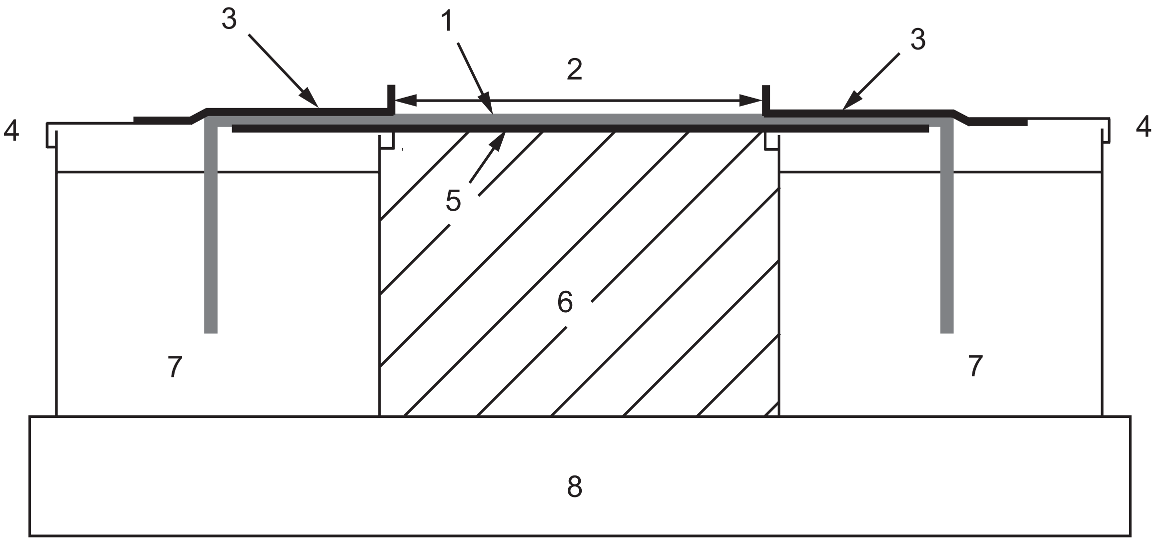
where

A is the active evaporation area of the test assembly, in m^2;

p_a is the vapour pressure of the air in the test chamber, in Pa;

$p_{sat}(\theta_a)$ is the saturation vapour pressure at the temperature of the test chamber, in Pa.

Evaporation from the edges of the test specimen is neglected as the thickness of the wick fabric is usually less than 0,5 mm. The temperature of the wick surface will be a little lower than the temperature of the test chamber due to evaporation, but, as this will also be the case for commercial piping installation, the test method described will give realistic values.



Key

1 test specimen

2 evaporation area

3 tape

4 screw cap

5 plastic foil

6 plastic foam

7 jar

8 tray

Figure B.2 — Test assembly

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ICS 91.140.01;91.120.10

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